Performance Analysis of Voltage Regulating Relays with Circulating Current Control Algorithms Using Hardware-In-Loop Real-Time Simulator Techniques

By

Thabo Modisane

In fulfillment of the Masters degree in Electrical Engineering, faculty of Engineering, University of KwaZulu-Natal.

As the candidate's Supervisor I agree/do not agree to the submission of this thesis.

Supervisor: Prof. B.R. Rigby

Signed………………….. at Durban on this………day of ………………

DECLARATION

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ACKNOWLEDGEMENTS

I would like to thank Eskom for awarding me a bursary to further my studies as well as Eskom TESP, THRIP, Durban University of Technology and the Department of Science and Technology for their support during the period this research was conducted. I would like to thank Prof. B. Rigby for his patience and support during the period when this research was conducted as well for his unwavering support during the period of compiling this thesis. I deeply appreciate the support I received from the staff of Eskom Distribution in the Eastern Region as well as the support I received from the technical staff from the University of KwaZulu-Natal.

I would also like to thank my fiancé, Ziphokuhle Zulu, for her support during the period when I carried out my further studies as well as for the encouragement she gave me when challenges seemed to be obstacles. Finally I would thank my friends and colleagues for their encouragement and support during the period of compiling this thesis. Most especially, I would like to thank Mr. Tumi Lekhela for his support and Mrs. Sphindile Sikhosana for assisting with proof reading of the Chapters in this thesis.

ABSTRACT

Electrical power distribution networks are required to provide power to customers at near-constant voltage levels in order that the customers' equipment operates with acceptable levels of performance and efficiency. However, as the power demanded by the customers varies during the day, the changing volt drops in the distribution networks mean that the voltage at the customers' load would likewise vary considerably if the voltages in the distribution network were not actively controlled. There are various methods that are used in industry in order to correct these voltage variations, such as boosting the bus bar voltage using tap-changing transformers, using shunt capacitors, or using single step voltage boosters on a distribution feeder. This thesis focuses on one particular method of voltage control, that is the use of on-load tap-changing transformers.

In industry, various control schemes are employed using commercially available relays in order to control tapping up or down of a transformer tap changer. In general, it is a relatively easy and well understood task to make use of such commercially available relays to automate the on-load tap changers on distribution transformers so as to regulate voltages to meet the demands of the utility practice. However, the issue becomes more challenging and less well-understood when multiple transformers are connected in parallel. One of the challenges that arises when on-load tap-changing transformers are connected in parallel, and these transformers are tens of kilometers apart, is that of circulating reactive currents that may flow between the transformers if their tap-changers are not carefully coordinated. Modern numerical relays for control of on-load tap-changing transformers provide a number of advanced algorithms, some of which allow control of circulating reactive currents without direct communication between the transformers.

This thesis examines the performance of one particular, commercially-available relay when used to control voltage and circulating currents in a real-time simulation model of an actual distribution network in the upper south coast region of KwaZulu-Natal. The thesis first derives and verifies a detailed simulation model of the voltage regulating relay itself, both in order to better understand the operating principles of the relay, as well as for future use by utility engineers who do not have access to a real-time simulator.

The thesis then examines the performance of the actual relays when connected in a hardware-in-loop arrangement with the real-time simulation model of the upper south coast distribution

network. The thesis presents some specialized real-time techniques and models that have been developed in order to conduct the studies into the relays' performance under realistic conditions in a distribution network. With the aid of these techniques and models, the hardware-in-loop simulator studies consider the performance of the relays in regulating both voltage and circulating current under a range of practical conditions in the network. In particular the studies consider the response of the relays to realistic changes in the size and power factor of the load on each transformer over a typical 24 hour period, and attempt to determine appropriate settings for the control algorithms in each regulating relay.

The results in the thesis show that the relays are able to regulate both voltage and circulating current without the need for inter-relay communications, when the loads in the distribution system are assumed to have constant power factors. Under more realistic conditions, when the loads in the distribution system are time varying (both in magnitude and power factor), the results show that the regulators do not perform adequately when their circulating current algorithms are set so as to assume fixed network power factors at each on-load tap-changing transformer. However, further studies show that if the adaptive network power factor tracking feature provided on the regulators is enabled, it is possible to set the regulators to achieve acceptable performances, even under the fairly wide variations in network loading conditions experienced in practice in the particular distribution system under study.

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CHAPTER ONE

Introduction

1.1 Background

One of the key objectives of a distribution network is to provide power to customers at voltage levels for which appliances and equipment such as motors or arc furnaces will operate with acceptable levels of performance and efficiency. Poor performance and low efficiencies of such equipment can result in loss of revenue. When customers have constant-power characteristic loads, that are relatively independent of voltages, a drop in system voltage will result in an increase in the customer's load current, which can lead to further volt drops in the supply system.

An increase in load current causes over heating of equipment, such as motors. Excessive heating for long periods results in insulation failure. It is also important to protect equipment from overvoltages, even though this is a rare phenomenon in distribution networks. When the maximum design voltage is exceeded, overvoltages can also result in insulation failure.

The dynamics of an electric power system are slow when it is operating under quasi steady state conditions, hence, significant changes in the system voltage level may occur over long periods before it is necessary to correct the voltage levels. Maintaining a constant voltage level on a power system is called voltage regulation. Voltage limits are set by utilities in order to standardize the maximum allowable voltage drops on a power network.

Within Eskom, the South African electric power utility, the current practice is to ensure that the maximum steady state flux level on distribution transformers is kept below 105% and that the voltage limits fall within ±7.5% of nominal for medium voltage customers [1]; these limits are set based on the NRS 048 document [2], which stipulates that the allowable voltage variation in a distribution network is ±5% of nominal voltage.

There are various methods that are used in industry in order to correct these voltage variations, for example: boosting the bus bar voltage using tap changing transformers, using shunt capacitors or by using single-step voltage boosters on a distribution feeder. This thesis will concentrate on voltage regulation at the bus of an interconnected network using on-load tap changing transformers. In industry, various control schemes are implemented via commercially-available relays in order to control tapping up or down of a transformer tap changer. A more detailed discussion of these relays will be provided later in the thesis.

In general, it is a relatively easy and well understood task to make use of such commercially-available relays to automate the on-load tap changers on distribution transformers so as to regulate voltages to meet the demands of the utility practice, and the legal requirements described above. However, the issue becomes more challenging and less well-understood when multiple such transformers are connected in parallel.

Whilst relays that permit parallel operation of on-load tap changing transformers are commercially available, there is little or no industry experience of how to determine the settings for such relays and of how they will perform under adverse network conditions. In large part this has been due to the absence of suitable tools with which to test the performance of these relays, once their settings have been designed, before commissioning them in the field.

This thesis aims to make use of real-time digital simulator hardware and software to allow closed- loop testing and performance evaluation of multiple voltage regulating relays on parallel-connected transformers in meshed topology distribution systems, as well as determining how to go about designing settings for such relays.

1.2 Review of the Technology of Voltage Regulation

1.2.1 General

There are relatively few commercial relays that are able to regulate secondary voltages of on-load tap changing transformers operating in parallel in a meshed distribution network. Two such products are the REG-DA from Eberle [3] and the M-2001C from Beckwith Electric [4].

Furthermore, the control algorithms used in these products are proprietary. As a result, there is not a significant amount of published technical literature on the theory and application of these products in industrial applications. However, this review highlights the information that is in the public domain in order to illustrate the research questions that the thesis aims to address.

1.2.2 Principles of Voltage Regulation

A distribution network consists of power lines that are used to transmit electric power to consumers. These power lines have resistive and reactive impedance distributed over their lengths and if electric current flows along the line, it results in a voltage drop across these impedances [5]. Power lines also have a capacitive effect which is distributed along the length of the line. This capacitive effect may be ignored for short lines.

When a voltage is applied at the sending end of the line, this applied voltage V_S is equal to the voltage V_R at the receiving end of the line during conditions of no load (assuming, as stated above, that the line capacitance can be ignored). When a load is connected to the line and electric current flows towards the receiving end of the line, the current that flows along the line causes a voltage drop across its impedance.

These voltage drops result in the receiving end voltage being smaller than the sending end voltage. As the loading on the line increases, the current that flows through the line increases which results in larger voltage drops over the line impedance and hence a smaller receiving voltage. This phenomenon is illustrated by Figure 1 below.

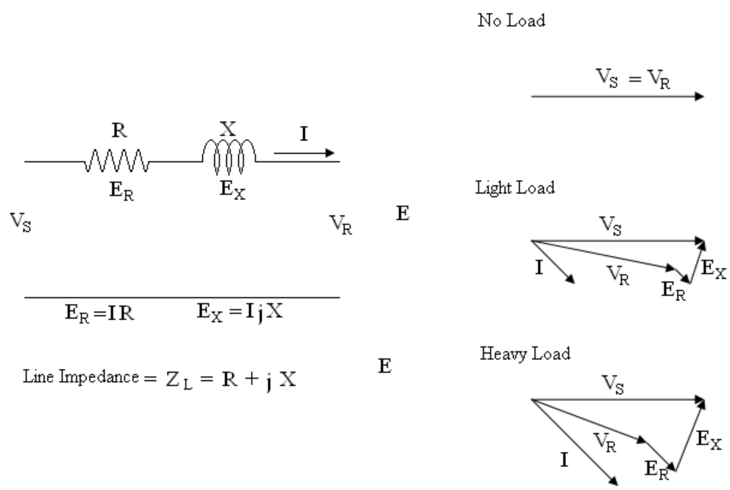

Figure 1: Voltage drop over a short electric power line (reproduced from [5]).

Contrary to the case of short lines, the capacitive charging effect on long distribution lines cannot be ignored during lightly loaded conditions. During no-load, as well as lightly-loaded conditions, the actual load current is generally smaller than the line's capacitive charging current and the vectorial addition of the two currents as shown by Figure 2, yields a resultant current that leads the sending end voltage [5].

It is important to note that the latter applies only to lightly-loaded lines or to lines supplying loads that have leading power factors, which is a rare phenomenon. Under normal operating conditions the load current that flows through the line has a lagging power factor. During conditions of heavy loading the resultant current will lag the sending-end voltage, resulting in a voltage drop across the line impedance and a reduced receiving end voltage as illustrated by Figure 2 [5].

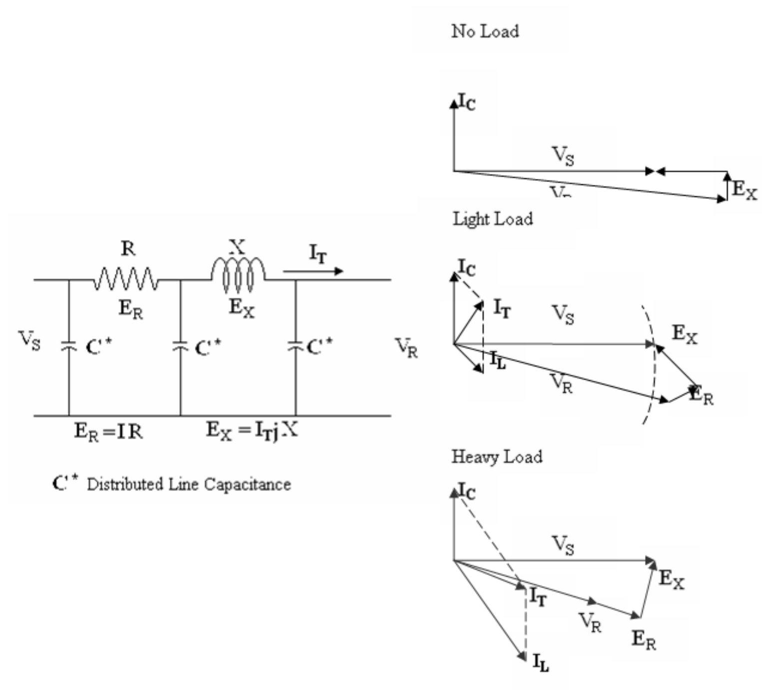

Figure 2: Voltage drop over a long electric power line (reproduced from [5]).

All the components of an electrical system, from generators to the power lines as well as transformers inherently have both series and shunt impedance [5]. Thus, the voltage at a customer's supply terminals will vary for different network configurations and variations in load conditions. According to regulatory standards mentioned previously these voltage fluctuations need to be kept within limits in order to enable proper operation of the electrical equipment, such as induction motors or furnaces that the consumers utilize. The distribution and transmission networks have equipment that is essential for the stability and control of these networks, such as static var compensators and line reactors which need to be operated at rated voltage. This shows that most electrical equipment is voltage dependent and it is important for the network voltages to be within the specified limits for network stability purposes as well as for proper operation of the electric equipment used by consumers.

There are various methods that are used in industry in order to correct these voltage variations, and some of these methods are boosting the bus bar voltage using tap changing transformers, using shunt capacitors to improve the substation power factor, or by using single-step voltage boosters on a distribution feeder to boost the line voltage from a specific point on the line.

The industry-standard specification on voltage regulation is ±10% voltage regulation in 32 steps, for single and three-phase regulators, which equates to 0.625% step size [5]. The single-phase regulators can be used to regulate the three-phase line voltage by connecting them in different configurations to achieve specific voltage regulation. When three single-phase units are connected in a closed delta configuration the maximum buck or boost increases from 10% to 15% as compared to an open delta configuration with two single-phase units [5].

Eskom's current standard practice is to ensure that the maximum steady state flux level on distribution transformers is kept below 105%, and that the voltage limits fall within ±7.5% of nominal for medium voltage customers [1]. In a similar manner to the single phase voltage regulators, these limits are set based on the NRS 048 document [2] which stipulates that the allowable voltage variations in a distribution networks are ±5% of nominal voltage [1]. At the substation busbar these voltage limits are controlled using electric power transformers equipped with on load-tap changers.

1.2.3 Tap changing transformers

An electric power system that operates in a quasi steady state is a classical illustration of slow dynamics, wherein long term trends may result in less than optimal operation if the initial system conditions are not maintained by controlling the system variables. For example, significant changes in the system voltage levels may occur over periods of time to an extent where action is required to improve them. Switching of shunt capacitors and operation of on-load tap changing transformers are two of the principal means of maintaining proper performance of the electric power networks in response to daily load cycles.

In order for the initial network conditions to be maintained, in particular the voltage levels, the secondary voltages of the transformers in the network must be controlled. Control of the secondary voltage of a power transformer is usually accomplished by the use of special devices which cause a contact to move on a switch so as to increase or decrease the number of turns on one side of the transformer and thereby regulating the secondary voltage of the transformer in a step-change manner [6]. The device that switches positions in order to regulate transformer secondary voltages is called an on-load tap changer (OLTC), due to its ability to switch positions while load current is flowing [6].

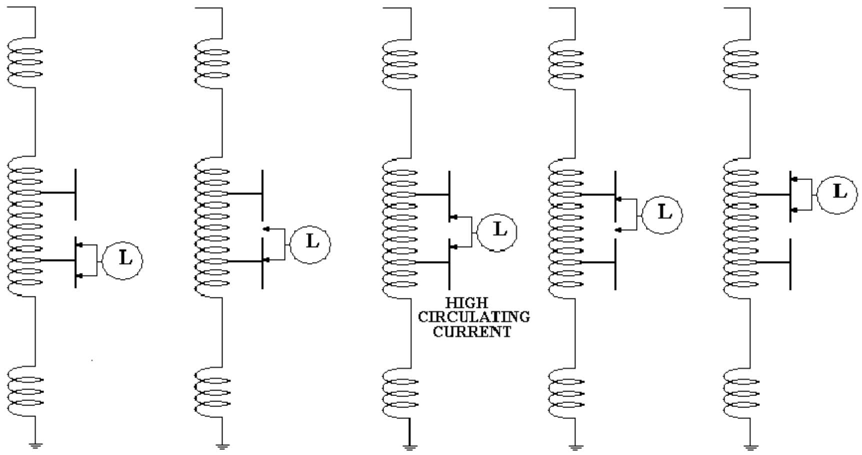

Figure 3: Transition of the OLTC during a tap change operation (reproduced from [6]).

It is essential that an OLTC operate as a make-before-break switch in order to keep continuous supply of electric energy to the load and to prevent arcing between the finger parts and the contacts as shown by Figure 3 above. There are different types of tap-changers which are used in industry. They are the resistance type, the reactance type and the vacuum interrupter. All of these products use different approaches to accomplish the same objective.

Arranging tappings on a transformer is one of the simplest and least expensive methods that is used in the electricity distribution industry in order to regulate the voltages of a distribution system. However, this method does present difficulties in the design of the transformers as well as unsatisfactory operating conditions. If the tappings of a transformer are arranged on the primary (high voltage) side of the transformer, it is then possible to arrange the tappings, within very fine limits, to give any desired voltage on the secondary (low voltage) side [6]. Taps are also normally placed on the high voltage windings because the tap changer will then handle less current and can be made smaller in size in order to reduce cost.

A basic on-load tap changing control scheme generally requires up to four set points and, of these, the first three are used with every installation [4]:

1. *Voltage level* – this is the desired value of the tap changing transformer's secondary voltage and hence the voltage value at the secondary of the voltage transformer (VT) used to make the secondary voltage measurement (typically 110V nominal).
2. *Voltage bandwidth* – this is defined as the range of voltage about the voltage level setting which will be acceptable by the controller as being within the set limits.
3. *Time delay* – a time delay is set intentionally in order to avoid tap changer operations for short durations of voltage dips below the set limits.

4. *Line drop compensation (LDC)* – the line drop compensation is set to compensate for the voltage drop in the downstream feeder under high loading. This is usually separated into two components, namely, the resistive and the reactive voltage drop on the line. In effect, the use of LDC allows a voltage some defined electrical distance into the distribution system to be regulated instead of regulating the secondary voltage at the transformer itself.

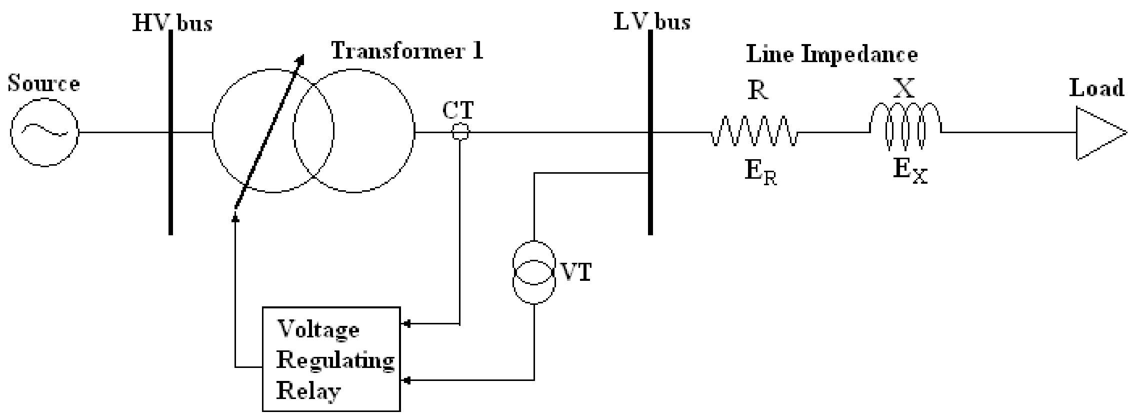

Figure 4: A radial distribution network.

Figure 4 shows the network components of a simple radial distribution network. Transformer 1 supplies a load via a reticulation feeder that has certain impedance. The voltage regulating relay regulates the LV bus voltage so as to ensure that the voltage at the load is within acceptable limits. The regulator does this by comparing the measured voltage to the set voltage and thereafter tapping the transformer in the direction that would bring the voltage to within the set limits.

In the case where the LDC setting has been implemented, the relay would use the measured voltage and the measured network currents, together with the line impedance, to calculate the voltage at the load end of the line. This voltage is compared to the set voltage and again the voltage regulating relay would tap the transformer in the direction that would bring the voltage at the load to within the set limits. The phasor diagram of the network voltages and currents is shown by Figure 5 below. It shows how the bus voltage is determined from the measured voltage and currents so as to regulate the voltage at the load end.

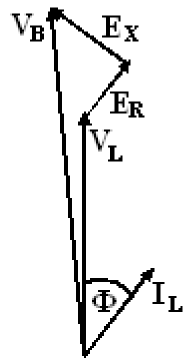

Figure 5: Network voltage and current phasors.

As discussed previously, the NRS 048 document stipulates that a utility must supply a voltage that is within certain limits to its customers. Figure 5 shows how the voltage drop across the line is compensated by regulating the LV bus bar voltage V_B so as to ensure that the voltage at the load V_L is within the stipulated limits.

It is sometimes essential to operate two transformers in parallel. Such a need often arises when the load connected to the network requires more power than that of an existing transformer or when network security is of great importance. When two on-load tap-changing transformers are operated in parallel, control of the bus voltage becomes more complex.

When two parallel transformers are at different tap positions, circulating current can flow between the transformers. This circulating current can lead to incorrect tapping of transformers which could result to overloading of one of the transformers. This concept of circulating current will be discussed in detail in the following chapter.

The network that is shown by Figure 4 is a simple distribution network. It often occurs that the network is meshed and has a number of transformers that feed into the network. It then becomes even more complex to regulate network voltages of such networks. The situation is further exacerbated when the transformers are tens of kilometers apart.

Previously when only the electromechanical relays were available for control of variables of an electrical network, it was difficult to control multiple variables using a single relay because of the design of the relays. The digital controllers that are available today are able to calculate the network variables and therefore have made it possible to implement more set points than those mentioned above as criteria for voltage regulation. For example, there are master-slave or master-follower algorithms that regulate only the bus bar voltages, and there are those that additionally take the circulating reactive current between parallel transformers into consideration.

1.2.4 Commercially Available Algorithms

There are several techniques for regulating the secondary voltage of transformers that are operated in parallel in order to minimize circulating reactive current between them. The methods that are provided by the M-2001C from Beckwith Electric are largely for use in a substation where transformers are a few meters apart. These methods are briefly explained below.

- *The negative reactance paralleling method* – this method is generally used as a short-term emergency solution to paralleling on-load tap changing transformers [6]. It consists of setting the line drop compensation (LDC) reactance setting to a negative value and results in the parallel transformers being biased according to their reactive power flow. A transformer with a higher tap position will have a higher reactive power flow than paralleled transformers at lower tap positions. The negative reactance setting will cause the next tap operation of the transformer with a higher tap position to be in the direction to equalize the reactive power flow of the transformers. It should be noted that the transformer with the higher tap position will be the only one that taps down and this action will result in the bus voltage being lower than the set voltage.
- *The master/follower paralleling method* – this method operates so as to keep the paralleled transformers at the same tap position. One voltage regulating relay takes over control while other relays follow its position commands. There is a feedback scheme that is required to confirm to the controlling relay that the following units have operated as instructed, and if that feedback is not received, the controls are set to lockout further operations.
- *The power factor paralleling method* – this method operates so as to keep a constant power factor at each bus of the parallel transformers. The power factor method does not bias the controls to operate but it blocks the tap changer from operating in the wrong direction based on the power factor. The power factor method will result in the transformer with the highest active power loading also having the highest reactive power loading.
- *The circulating current paralleling method* – this method assumes that there is a maximum allowable amount of circulating current between parallel transformers for

all system operating configurations, and that any changes in the circulating current are a result of an undesirable change in the relative tap positions of the parallel transformers. The drawback with the circulating current paralleling method is that in order to separate the circulating current from the load current separate equipment is required.

- *VAr balancing method* - This method acts as to share the reactive power flow through the transformers, according to their sizes, regardless of the real power flow [6]. Like in the circulating current method auxiliary equipment is used in order to separate the circulating current from the load current.

REG-D relays from a-eberle provide specific control options for a range of possible parallel transformer connections: closely connected transformers in a substation (with direct Ethernet connections between the regulators) and wide area control applications where there are significant distances, and no communications, between the transformers. The algorithms provided by the REG-D relays are summarized below.

- *Master-slave method* - this method operates so as to keep the paralleled transformers at the same tap position. One voltage regulating relay takes over control while other relays follow its position commands. The slave relay is equipped with additional intelligence that allows it to read the tap position of the master via an energy local area network (E-LAN) and it can independently position itself to match the master's tap position.
- *Circulating reactive current method* – In this method the circulating reactive current is determined by measuring the currents at the infeed of the transformers and it is minimized by targeted tapping of the transformer.
- *The Δ $cos\varphi$ method* – this algorithm monitors both voltage and current at the secondary terminals of the transformer and calculates the power factor of the network as seen by that transformer. The difference between this measured power factor and a set-point power factor for the network at that transformer is used as an indirect measurement of the presence of circulating reactive current in the transformer.

This review has briefly described the different technologies that are available for controlling circulating reactive currents between parallel transformers. The majority of these algorithms are designed to regulate voltages and circulating currents between transformers that are in the same substation. It becomes a challenge to regulate the secondary voltages of transformers that are kilometers apart, as well as to limit circulating reactive currents that may flow between them.

The Δ cosφ method is a distributed control scheme that may be used to control secondary voltages of on-load tap changing transformers that are tens of kilometers apart. In a master-slave tap changing algorithm, one regulator takes over control while the other regulators follow its position commands. The drawback with this control algorithm is that there must be a dedicated link between the regulators for communication between their relays, which implies that in a meshed network where transformers are tens of kilometers apart it would not be attractive for economic reasons [7].

In the algorithms that minimize circulating reactive current, the current is measured at the secondary terminals of the transformers and it is minimized by targeted tapping of the transformers. This thesis will investigate how the Δ cosφ control algorithm, which is available in the REG-DA relays, is able to control both the voltages and the circulating currents that may flow between parallel transformers in a realistic electrical distribution network.

1.3 Thesis Objectives

The South African utility Eskom operates its distribution networks mostly in a radial network topology. Radial network topologies do not present many stability challenges to an electric system. It is relatively easy and simple to regulate network voltages in radial network topologies.

In meshed network topologies circulating reactive currents can flow between transformers that are at different tap positions. This concept of circulating currents and how they affect voltage regulation in meshed network topologies will be discussed in Chapter Two. These currents present difficulties in regulation of network voltages.

The electromechanical relays use the bus bar voltages and network currents as inputs to control the network voltages but they are limited to only voltage control. The introduction of electronic relays allowed engineers to have more parameters to set in order to regulate network voltages. These relays also measure both bus voltages and network currents but over and above these measurements, they are able to determine other network variables like the network power factor, apparent power etc. within a single relaying unit. This diversity of electronic relays allows engineers to use the variables that can be calculated by the electronic relays in conjunction with the measured network voltage as criteria for voltage regulation.

There are many relays available in industry that control on-load tap changers in order to regulate the secondary voltages of distribution transformers. A number of the relays that are available are able to control circulating currents that may flow between transformers which are connected in parallel within a substation yard. As mentioned in the preceding section, the algorithms that many of these relays use to regulate both voltage and circulating currents between parallel transformers require communication links between the relays as well as separate equipment for separating circulating current from load current. These requirements present a challenge in the control of circulating currents and regulation of network voltages in a meshed network topology where the transformers are tens of kilometers apart.

Eskom is currently using the REG-D relay for regulation of transformer secondary voltages. The REG-D relay is also able to control both circulating current and regulate voltages using the $\Delta\cos\varphi$ algorithm, but this algorithm has the advantage that it does not require any communication links between the relays in the network. This feature of the REG-D relays would allow for cost-effective regulation of network voltages and control of circulating currents in a meshed network topology where the transformers would be tens of kilometers apart. It is for these reasons that this particular relay has been chosen for a detailed study in this thesis.

The aim of the thesis is to establish how the $\Delta\cos\varphi$ algorithm works, to establish appropriate methods for determining settings for this algorithm, and to establish its performance under practical conditions in a realistic distribution network.

1.4 Thesis Structure

In Chapter Two, the thesis describes the circulating current problem in more detail as well as the nature of the circulating current in meshed distribution networks. Methods of limiting the circulating currents in meshed distribution network topologies are then reviewed and thereafter the thesis describes in full detail the fundamentals of how the REG-D Δ cosφ algorithm approaches the circulating current problem. Chapter Two also gives a review of the Real-Time Digital Simulator (RTDS), which is tool that is used for closed loop testing of the REG-D relay algorithms and settings in the thesis.

In order to fully understand how the Δ cosφ method operates, detailed simulation models of its voltage regulating and circulating current control algorithms are developed in Chapter Three. These models are developed using the real time digital simulator. The response of the simulation model is then compared to the response of the hardware relays using a simple two transformer network, in order to validate the simulation model.

Chapter Four focuses on the application of the REG-D relays in an actual distribution network, at a fixed operating point, in order to understand their performance and how to determine their settings. In this chapter the response of the simulation model of the REG-D relay is again compared to that of the actual relay in order to verify that the simulation model has been developed correctly. The simulation model is then used to determine how to go about designing the settings for the relay, as well as the impact these settings will have on the network.

Chapter Five studies the response of the REG-D relays to more realistic network conditions. In this chapter actual energy measurements obtained from Eskom are used to determine the typical behavior of the loads in the network under study over a 24 hour period. Custom real-time simulator models are developed to replicate the time-varying behavior of both the active and reactive components of power at each of the load points in the network. Chapter Five demonstrates the challenges that are presented to the Δ cosφ method by the varying network power factor as the load changes over a 24 hour period. Arising from the studies in Chapter Five, a method is proposed for choosing the network power factor set point within the Δ cosφ algorithm in order to minimize these challenges.
Finally, Chapter Six summarizes the main results from the studies carried out in the thesis and suggests further research that could be undertaken in future.

1.5 Main Achievements and Findings of the Thesis

The main findings and achievements of this thesis can be summarized as follows.

A detailed simulation model of the relevant REG-D relay's algorithms has been developed using the Real-Time Digital Simulator (RTDS) and these algorithms are verified in the thesis. The response of the REG-D relay to changes in the network topology is investigated as well as its response to realistic variations in network loading conditions. Techniques for studying the performance of the relays over long time periods using the RTDS are developed. The effects of different REG-D settings on the response of the relays during realistic network conditions are investigated and the results are used to propose procedures for arriving at suitable settings for the relay's Δ cosφ algorithm.

1.6 Research Publications

The findings of the thesis have been published in the proceedings of international conferences [21, 23, and 24] as well as local conferences [20, 22].

CHAPTER TWO

The Circulating Current Problem

2.1 The Origins of Circulating Current in Distribution Systems

When transformers are operated in parallel as shown by Figure 6, it is essential that they continue to serve their basic function of controlling the load bus voltage as prescribed by the settings of the voltage regulating relay. It is desirable, for a distribution network, that transformers be operated in parallel and to have them connected in a meshed configuration in order to benefit from the additional operating flexibility and security of supply that such arrangements allow in case there are equipment outages.

However, parallel-connected transformers must also act so as to minimize the circulating reactive current between them and the above mentioned actions must operate correctly in a multiple transformer application regardless of system configuration changes. Circulating current between parallel transformers is as a result of inappropriate operations of transformer tap changers.

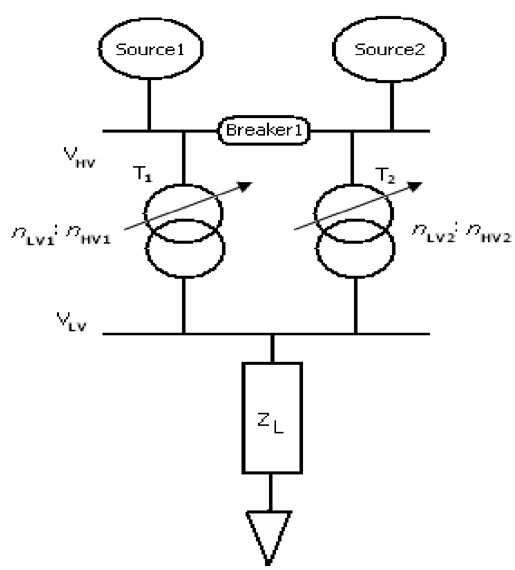

Figure 6: Transformers in parallel

The origin of the circulating current problem is illustrated by the simple case of two similar transformers connected in parallel as shown by Figure 6. When the two transformers with equal impedances are at different tap positions such that their turns ratios are different, circulating current will flow between the two transformers. This is due to the fact that their internal voltages V_A and V_B will be different, as shown by Figure 7.

Since the impedance of a transformer is highly inductive it can be concluded that circulating current between parallel transformers would be reactive current. For the case of two parallel transformers shown in Figure 6, the approximate equivalent circuit shown in Figure 7 can be used to derive voltage and current phasor diagrams to illustrate the circulating current problem. The reactive circulating current in Figure 7 is given by [7]:

$$I_{CIRC} = \frac{V_A - V_B}{j(X_{T1} + X_{T2})} \tag{1}$$

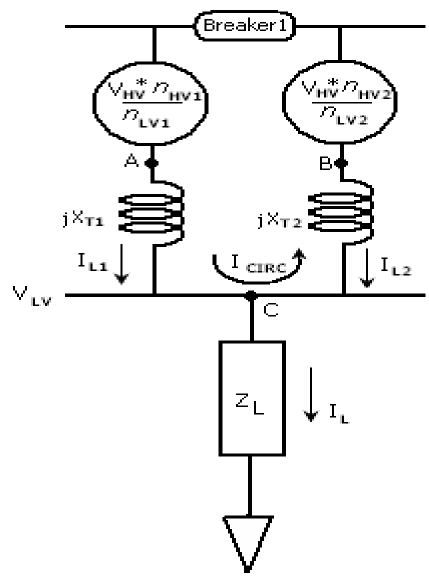

Figure 7: Approximate equivalent circuit of transformers in parallel

In Figure 7 the breaker on the HV bus bar is closed and hence voltages V_A and V_B are in phase, as shown by Figure 8, but since the transformer impedances are highly reactive the circulating current lags the voltage phasor $(V_A - V_B)$ by 90º [7]. From Figure 7 it can be seen that the circulating reactive current adds to the load current component of the transformer with higher internal voltage and is subtracted from the load current component of the transformer with lower internal voltage, thus resulting in expressions for total currents in each transformer as follows.

$$I_{T1} = I_{L1} + I_{CIRC} \tag{2}$$

$$I_{T2} = I_{L2} - I_{CIRC} \tag{3}$$

Note that in Figure 8, the difference in amplitude between the transformer internal voltages V_A and V_B as a result of their different tap positions (and hence in the two load current components I_{L1} and I_{L2}) is deliberately made significant for ease of illustration.

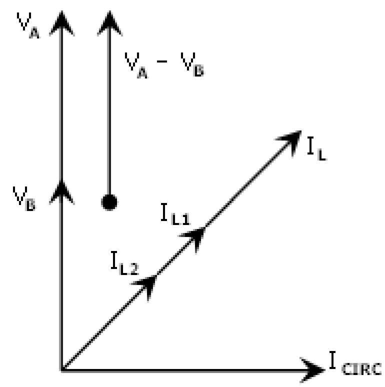

Figure 8: Phasor diagram showing circulating current

Circulating reactive current can result in a significant increase in the apparent power loading of an individual transformer for a given system active power loading. When the system is heavily loaded, unwarranted loading on one of the transformers that is caused by the circulating reactive current, can cause that particular transformer to trip out on overcurrent or on oil temperature. This will result in the remaining transformer/s being overloaded. Circulating reactive currents also cause a loss in sensitivity of the transformer's secondary voltage to tap changes at the affected transformers under conditions of light loading.

The topology of the transformers shown in Figure 7 is common at substations with multiple transformers connected to the same bus. The circulating current problem is easy to solve for this configuration as the transformers are typically only a few meters away from each other and the voltage regulating relays would be in the same substation. Hence these relays would be able to communicate via an Ethernet connection in order to coordinate their tap positions so as to avoid creating circulating currents. Some of the commercially available relays (for example the REG-D [3]), are able to regulate multiple transformers by using a master-slave algorithm in order to ensure that there is no circulating current between transformers.

The circulating current problem becomes more challenging when multiple transformers are connected in parallel in a wider distribution network, where transformers are tens of kilometers apart. For these widely meshed networks it is technically feasible to install communication links between regulating relays in order to implement the master-slave algorithm to solve the circulating current problem but it is uneconomical to do so.

The challenge that is mentioned above is illustrated by Figure 9, which shows an 88 kV and 22 kV Eskom distribution system with three 88/22 kV on-load tap changing transformers at substations U, S and W [7]. Part (a) of Figure 9 shows the topology of the system when the breakers of the lines connecting the substations are normally opened (N/O). In this case the topology of the network is radial and each transformer tap changer can independently regulate its own secondary voltage with no requirement for additional supervision. Part (b) of Figure 9 shows the topology of the network with all the line breakers normally closed (N/C). The network topology is now meshed which is advantageous for a utility in terms of equipment and supply redundancy.

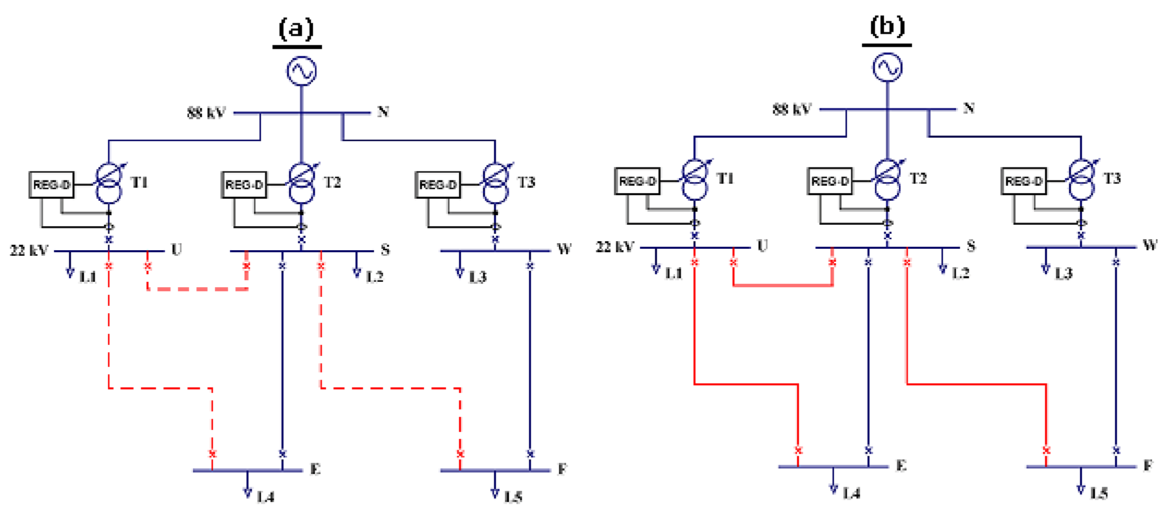

Figure 9: Eskom- Eastern Region south coast distribution network [7].

In this meshed topology, where the transformers are interconnected, circulating current will be able to flow between transformers if their tap settings are not kept within a few positions of each other. This circulating current will be limited by the impedances between the transformers. However, as mentioned above, the installation of communication links between substations to manage such coordination, although technically feasible, is uneconomical.

In such cases special control algorithms are needed at each transformer to prevent circulating currents while also regulating voltage without direct knowledge of the tap positions of the other transformers in the system. It is this problem that is of particular interest in this thesis, since many such applications exist in Eskom's distribution networks.

2.2 The REG-D Approach to Circulating Current Control

As explained in Chapter One, the particular relay considered for study in this thesis, the REG-D, provides an algorithm known as the $\Delta\cos\varphi$ algorithm to regulate circulating currents in distribution systems such as that shown in Figure 9. This $\Delta\cos\varphi$ algorithm is based on the fact that one of the symptoms of circulating reactive current between parallel tapchanging transformers is a change in the power factor at the terminals of each transformer from the actual power factor of the distribution network and its loads [7]. This algorithm can be used in widely meshed distribution networks where transformers are tens of kilometers apart and cannot communicate with each other. The operator sets the network power factor ($\cos\varphi_{set}$). The circulating reactive current is then calculated as follows:

$$I_{CIRC} = I_T \sin\varphi_{set} - I_T \sin\varphi_{act} \tag{4}$$

Where:

I_{CIRC}	is the calculated circulating current
I_T	is the current through the transformer
φ_{set}	is the setpoint power factor angle
φ_{act}	is the measured power factor angle

When the calculated transformer circulating reactive current is higher than a user defined set point then the transformer should tap down, and vice versa. The $\Delta\cos\varphi$ algorithm is superimposed onto the voltage regulating algorithm as follows [3]:

$$Y_U = (U_{act} - U_{set})/\Delta U_{perm} \tag{5}$$

$$Y_P = I_{CIRC}/I_{CIRCperm} \tag{6}$$

$$Y = Y_U + Y_P \tag{7}$$

Where:

U_{act}	is the measured secondary voltage
U_{set}	is the setpoint of the secondary voltage
ΔU_{perm}	is the permissible voltage regulation deviation
$I_{CIRCperm}$	is the permissible circulating current

Y_U is the voltage error signal

Y_P is the circulating current error signal

Y is the final, combined error signal from the voltage and circulating current regulators

When the combined error signal $Y < -1.0$, the control command would be to increase the transformer tap position. When the combined error signal $Y > 1.0$, the control command would be to decrease the transformer tap position. The detailed structure and performance of this particular algorithm is investigated in the thesis. Although from a purely academic point of view, it may be attractive to study and compare the performance of more than one approach (product) for regulating circulating current, one of the principal drivers behind this research project has been Eskom's need to better understand the performance of the product that they are already committed to using in their distribution networks.

As part of the research study in this thesis, the REG-D relay has been modeled in detail in order to better understand how to design settings for the relay to operate effectively in a realistic distribution network. This simulation model of the REG-D relay was developed and tested using the real-time digital simulator. The real-time digital simulator also provides a platform for testing the actual REG-D relays themselves when connected hardware-in-loop with a real-time simulation model of the distribution network. The thesis also considers the performance of the REG-Ds in the study system of Figure 9 using this hardware-in-loop testing approach.

2.3 Conclusion

It has been discussed in the previous sections that circulating reactive currents will flow between transformers in a distribution network when the transformers are at different tap positions. These circulating currents are limited by the impedances between the transformers. When the circulating currents that flow between parallel transformers at different tap positions are not controlled adequately, these circulating currents could result in one of the transformers being overloaded and thus tripping out on overload or oil-temperature protection.

There are various commercially available relays that are able to regulate both voltage and circulating currents between transformers. The majority of the algorithms that most of the relays implement to regulate both voltage and circulating currents require a communication link between the relays. When transformers are tens of kilometers apart and are connected via a meshed network, it becomes uneconomical to have a communication link between the relays to allow the relays to regulate the transformers secondary voltage and circulating currents.

This chapter has discussed one particular relay that is able to regulate both secondary voltage and circulating currents of parallel transformers without the need for a communication link between relays, the REG-D relay from a–erbele. The REG-D relay has a $\Delta\cos\varphi$ algorithm for regulating circulating current, and one of the principal drivers behind this research project has been Eskom's need to better understand the performance of this product (the REG-D relay) and the application of its $\Delta\cos\varphi$ algorithm in their distribution networks.

It is fairly well understood how to design settings for the voltage regulating algorithm of the REG-D relay but there are limited guidelines and operational experience to rely on to design settings for the $\Delta\cos\varphi$ algorithm. In order to better understand how to design settings for the $\Delta\cos\varphi$ algorithm a detailed model of the REG-D relay was developed for use on a real-time digital simulator, and this detailed model development is discussed in later chapters of the thesis. However, the following chapter describes the real-time digital simulator itself, since this platform has been used throughout the investigations in this thesis, both for real-time modelling of the REG-D relay algorithms, and for subsequent hardware-in-loop testing of the physical relays themselves.

CHAPTER THREE

The Real Time Digital Simulator

3.1 Introduction

In the not so distant past, analogue protection and control devices such as induction disks could be tested with confidence on heavy current test benches using power frequency signals that were transformed down from the mains. These devices had operating times of 100ms or more and that meant that testing of such equipment during fault transients was not possible [9]. With the evolution of relays from induction disk or balanced beam relays to induction cup, moving coil and later to electronic relays, which have near instantaneous operating times, it was then necessary to at least accurately model the exponential component of fault waveforms.

It became apparent that the speed of operation of relays and that of maloperation went hand in hand, but system expansion required faster operation in order to maintain stability [9]. Producing test signals for the relays became a challenging task since it was necessary to adequately represent the fault "noise" signal components both on the relay input signals and electromagnetic interference from the relay environment had to be taken into account.

The problem of modeling the fault signal was overcome with the development of EMTP (Electromagnetic transients program). Fault waveforms could be recorded digitally and played back in real time at the relay under test via programmable Digital to Analogue (D/A) converters [9]. This testing allowed realistic input signals obtained from detailed off-line models, to be applied to relays for testing but did not enable any study of the *interaction* between the relay and the power system.

This meant that it was possible to study the open loop response of a relay to accurate reproduction of fault signals, but not the system's response to the relay's subsequent actions, or, importantly, the interaction of multiple relays with each other in a full protection *scheme* as a result of such faults. This limitation with traditional off-line testing is of particular importance when studying a product such as a REG-D, since when it is set to regulate circulating current it does not act either open-loop or on its own, but rather in concert with all the other (possibly) remote REG-Ds in the network.

3.2 Interfacing a real-time simulation to external hardware

The RTDS is a time domain simulator that can be used to interface physical power system control and protection equipment such as relays, in order to test the performance of such equipment under realistic field conditions. An RTDS system comprises one or more 19" racks each of which contains multiprocessor DSP cards that perform the mathematical computations required to model the user defined power system. The processors are equipped with multi-channel 16-bit, high speed optically isolated digital to analogue converter (DAC) channels [8]. These are used to interface the simulator to equipment being tested. Digital signals can be sent to and from the simulator via TTL-level digital input and output ports on the processor cards.

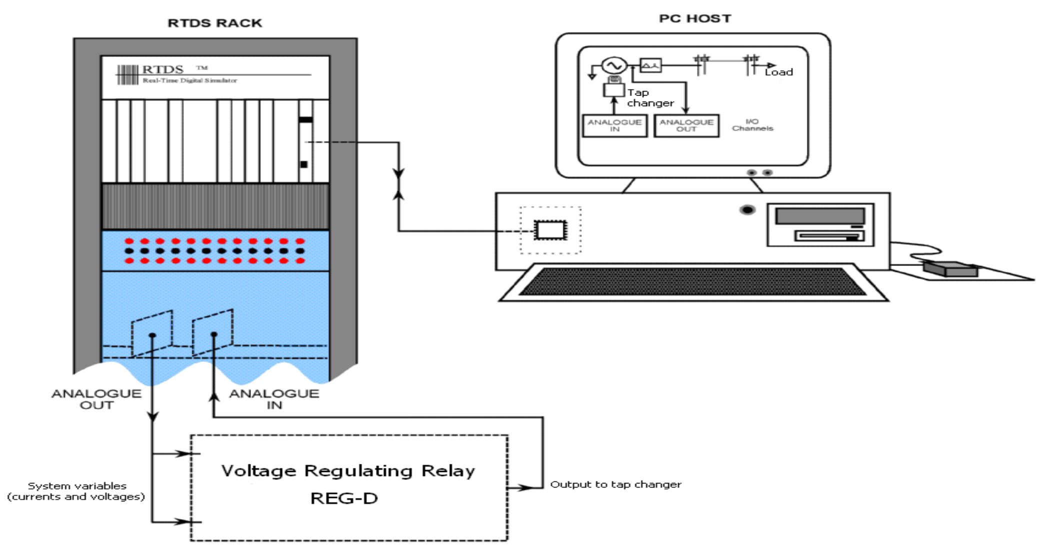

Figure 10: Closed-loop testing of a voltage regulating relay on an RTDS system [7]

The user develops power system models in a graphical user interface (GUI) called DRAFT on a separate personal computer (PC) host as shown in Figure 10. The component models used to construct the power system model can be refined through their parameters to accurately model the desired power system scenario or control logic. These models are then compiled and downloaded to the RTDS rack where they run in real time. The user can view the simulation results or interrogate the simulation on a graphical user interface called RUNTIME.

When the simulation is running certain system variables can be sent to analogue and digital output ports on the RTDS rack. In the case of testing voltage regulating relays it would be possible to export the voltages and currents at the secondary of a transformer to analogue outputs. It is also possible to send variables to the real-time model of the system from the relays via the digital or analogue input ports, for example, when a raise or lower tap position command is sent to the tap changer within the real-time simulation from an external relay under test.

Hence by connecting a number of REG-Ds in closed-loop with a real-time model of a study system using the approach shown in Figure 10, it is possible to test the behaviour of each REG-D when regulating its own transformer, as well as the interactions between the REG-Ds via the power system in response to realistic network currents and field conditions.

3.3 Previous Technical Investigations into Coordinating Multiple Tap Changers

3.3.1 Introduction

Very little work has been published in the technical literature on the subject of coordinating tap changing relays. This may be in part because, until very recently, the tools necessary to carry out such investigations simply did not exist. With the arrival of real time digital simulators, it is now possible to conduct detailed investigations of the performance of multiple tap changing controllers under laboratory conditions.

3.3.2 RTDS real time simulators

The RTDS is a time domain simulator that can be used to interface physical power system control and protection equipment such as relays, in order to test the performance of such equipment under realistic field conditions. The system comprises one or more 19" racks each of which contains multiprocessor DSP cards that perform the mathematical computations required to model the user defined power system.

The processors are equipped with multi-channel 16-bit, high speed optically isolated digital to analogue converter (DAC) channels [8]. These are used to interface the simulator to equipment being tested. Digital signals can be sent to and from the simulator via TTL-level digital input and output ports on the processor cards. The RTDS system can be used for closed loop testing of one or more power system protection, automation and control devices using highly detailed EMT – type power system models.

Some research has been done [10] on multiple automatic voltage control (AVC) relays in a radial network using a Real Time Digital Simulator, in order to demonstrate the response of the AVC relays with a selection of control strategies to different power system scenarios. In other words, in the work described in [10] the focus was on coordinated tapping between upstream and downstream series-connected voltage regulators in a radial system.

However, the aim of this thesis is to make use of the real-time digital simulator hardware and software to allow closed loop testing and performance evaluation of multiple voltage regulating relays on parallel-connected transformers in meshed topology distribution systems.

3.3.3 Testing Parallel Transformers using an RTDS

Prior to the work of this thesis, a preliminary investigation was carried out by others [7] for Eskom as proof of the concept, using an RTDS to demonstrate that REG-D relays can successfully be used to prevent circulating currents in the actual distribution system shown in Figure 9. However, this earlier work considered only one example network, and only one system wide loading condition [7]. The circulating current settings for the REG-D adopted in the study reported in [7] were determined using practical engineering judgement at this one network operating point.

No analysis was presented in [7] on the effect of the permissible circulating current setting on the voltage regulation performance. In addition, the performance of the REG-Ds under variable load conditions was not considered in [7]. The latter issue is particularly important because the method used to detect the presence of circulating current involves comparing measured network power factor at each point of control to a “desired” or set point power factor. However, a change in this set point power factor can occur as a result of actual changes in the power factor of one or more network loads, or even a change of the relative sizes of loads of different power factors at different points in the network. In other words, a REG-D that has been set to maintain a particular power factor in a distribution network would respond to a change in this power factor as though it is a result of circulating current flows, whereas such a change could be due to actual variation in network operating conditions.

Since the initial studies conducted in [7] were carried out, the manufacturers of the REG-D, a-eberle, have developed an adaptive algorithm to adjust the circulating current settings of the REG-D to track slow changes in actual network power factor. However, at the time this research thesis was started, it had yet to be seen how these algorithms would perform under realistic network conditions or what their limitations might be.

Another issue that was not considered in the studies in [7] is that of the performance of the REG-D in a distribution network where intentional topology changes occur e.g. where equipment or lines are removed temporarily from the network for maintenance. Once again, since the REG-Ds regulate circulating current by maintaining the power factor at their point of control to some set point, this set point itself may need to be adjusted to suit different network topologies.

In order to be able to test these control algorithms and their effect on the performance of the tap changers in a distribution network it is imperative to model the REG-D relay extensively and fully understand the effect of its settings and control limitations. Thereafter, methods of designing suitable settings for such relays suitable for operation under realistic network conditions can be proposed.

3.4 Conclusion

With the development of electromagnetic transients programmes it became possible to conduct detailed and accurate simulations of fault conditions and to record the simulated fault waveforms digitally. This development made it possible to test the performance of relays by playing the recorded waveforms back to relays in real time via programmable D/A converters. This meant that it was possible to test the performance of relays to accurate reproduction of fault signals but it was not possible to study the system's response to the relay's subsequent actions. Also, it was not possible to study the interaction of multiple relays interconnected in a distribution network.

After the development of EMT programmes, the Real Time Digital Simulator (RTDS) was developed. The RTDS is a time domain simulator that carries out detailed and accurate EMT-type simulations in real time; it therefore allows engineers to interface physical power system control and protection equipment such as relays directly to a detailed simulation model of the system as it is solved in real time. This approach allows closed-loop testing of real equipment connected hardware-in-loop with the detailed EMT model, in order to test the performance of such equipment under realistic field conditions. The RTDS also allows interrogation of the system during a simulation which means that engineers are able to download the system variables during a simulation for analysis.

The capabilities of the RTDS also allow users to develop their own real-time models of the inner algorithms of relays under test, so that the performance of these models can be compared to that of actual relays. These algorithmic models can then be exported to other simulation packages for use in off-line testing of relay settings. In the following chapter a real-time simulator model of the REG-D relay and its algorithms will be developed using the RTDS platform in order to better understand the reasons for the observed dynamic performance of the REG-Ds under practical conditions, and hence to determine how best to design settings for the $\Delta\cos\varphi$ algorithm.

CHAPTER FOUR

Software Modelling Of the REG-D Algorithms

4.1 Introduction

It has been mentioned in Chapter Two that the technology of voltage regulating relays has advanced to an extent that some of the relays that are available in the market are able to regulate both voltage and circulating current of a distribution transformer. Relays with such capabilities become necessary when a distribution network is operated in a meshed network topology and also when transformers are operated in parallel in a substation.

The reason that these relays are necessary for transformers that are operated in parallel is that transformers connected in this way inherently provide paths for circulating currents to flow between them when they are at different tap positions. These circulating currents could lead to incorrect tapping of some transformers and this could result in some of the transformers in the network being overloaded. This phenomenon will be made clear in Chapter Five.

According to [3], the circulating current regulation algorithms on the REG-D relay can be used to ensure that any changes in the tap position of a distribution system on-load tap changing transformer required to regulate its secondary voltage are carried out in coordination with the tap positions of the other transformers in the network. By so doing, the algorithms will ensure that the transformers in the network are kept within a few tap positions of each other thereby minimizing the flow of circulating reactive current between them.

The REG-D relay has several algorithms that control both voltage and circulating current. These are: the $\Delta I \sin\varphi$; $\Delta I \sin\varphi[S]$, Master-Slave, $\Delta\cos\varphi$ and the Master Slave Independent algorithms. The $\Delta I \sin\varphi$, $\Delta I \sin\varphi[S]$, Master-Slave and the Master Slave Independent algorithms are used to control on-load tap-changing transformers that are feeding onto the same bus. The $\Delta\cos\varphi$ algorithm can be used to regulate voltage and circulating currents of distributed transformers in a meshed network topology. The $\Delta\cos\varphi$ algorithm is most suited to applications where the transformers are kilometers apart because it does not require communication between the relays, whereas the other REG-D algorithms require a communication link between the relays.

The REG-D relay has been shown in the studies conducted by [7] to be able to regulate both voltage and circulating current satisfactorily, when it is used at distributed on-load tap changing transformers in a widely-meshed distribution system. In the studies conducted by [7] actual hardware REG-D relays were used in closed-loop with a simulation model of an Eskom Kwa-Zulu-Natal upper south coast distribution network running on a real-time digital simulator and the studies showed that the $\Delta\cos\varphi$ algorithm is able to regulate both circulating current and transformer secondary voltage when the distribution network is operated at a specific operating point.

The end goal of this thesis is to extend the scope of the studies conducted in [7] to better understand the performance of, and appropriate settings for, the REG-D relays in meshed networks. However, in order to understand how the relays operate and what effect their settings have on their operation, it is useful to develop a simulation model of the REG-D relay.

In order to verify the correctness of the simulation model, the performance of the simulation model was compared to that of the actual REG-D relay. An additional benefit of an accurate, verified simulation model of the REG-D relay is that it will allow engineers to test their settings off-line and have an understanding of how the relay would perform in a real distribution network using other simulation packages without needing the RTDS for every such simulation study.

4.2 The REG – D simulation model

4.2.1 Voltage regulating algorithm

The dynamics of an electric power system are slow when it is operating under quasi steady state conditions, hence, significant changes in the system voltage level may occur over long periods before it is necessary to correct the voltage levels. The REG-D relay regulates the transformer secondary voltage conventionally by comparing an input voltage measured by a voltage transformer to a set voltage, and after a certain time delay the relay computes what action to take.

This subsection will focus on discussing the REG-D's voltage regulation algorithm, as shown in Figure 11. The REG-D relay measures the transformer secondary voltage and the measured voltage is used as an input U_{act} to the voltage regulating algorithm. The voltage regulating algorithm subtracts the set voltage U_{set} from the measured voltage U_{act}, then this error result is normalized by dividing it with a set permissible deviation ΔU_{perm} and the result is the normalized voltage error signal Y_U. The normalized voltage error signal Y_U is an output of the voltage controlling algorithm and it is used to control the tap changing mechanism.

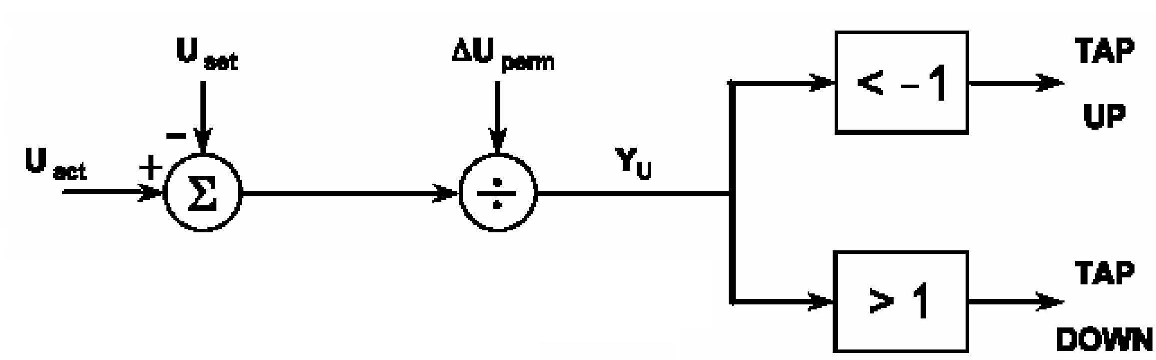

Figure 11: Voltage regulation block diagram.

If the normalized signal Y_U is less than negative one then the transformer will tap up one position and if it is greater than one then the transformer will tap down. Before the transformer taps up or down a time delay is included in the REG-D relay, to ensure that the relay does not take corrective action for short-duration transient changes in voltage levels. Figure 12 below shows the simulation model of the voltage regulation algorithm which was developed for use on the RTDS real time simulator. From Figure 12 it can be seen that the instantaneous measured line voltages are converted into an r.m.s. voltage magnitude which is the input to the voltage regulating algorithm.

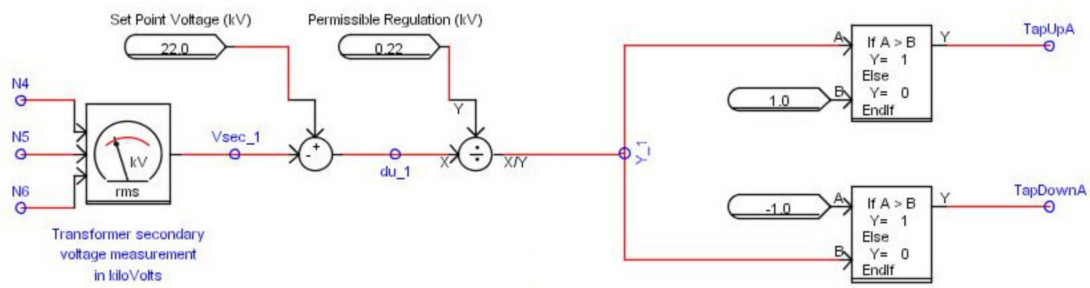

Figure 12: The real time simulation model of the REG-D voltage regulating algorithm.

Tap-changing transformers are designed to provide a specific percentage change in primary to secondary turns ratio for each change in tap position. In Eskom, it is standard to utilize distribution transformers with 17 tap positions, with tap position 5 that which would give nominal turns ratio. A transformer with 17 tap positions is designed such that each tapping can cause voltage to change by 1.25% of the nominal voltage. It is recommended by [3] that the permissible deviation setting should be set to be at least greater than 60 percent of the transformer voltage change for each tapping. This will ensure that the tap-changer is stable and it will not fluctuate around the set voltage.

As it was mentioned before, a distribution network may be subjected to different disturbances and normal load changes during a typical 24 hour load cycle. These disturbances will affect the network in various ways and therefore the voltage regulating relay should respond to the different disturbances accordingly. For a severe voltage drop the regulator should return the network voltage to within the set limits as quickly as possible.

Similarly, when the voltage drop is low to an extent where normal operation of electric equipment on the network will not be adversely affected, then the relay can take some time to allow the network to return to its normal operating conditions before any corrective action is implemented. There are time programs that the REG-D relay uses to determine the rate at which corrective action would be implemented after the network voltage deviates from the set voltage limits. The time programs are the “Const” time program and the “Integral” time program.

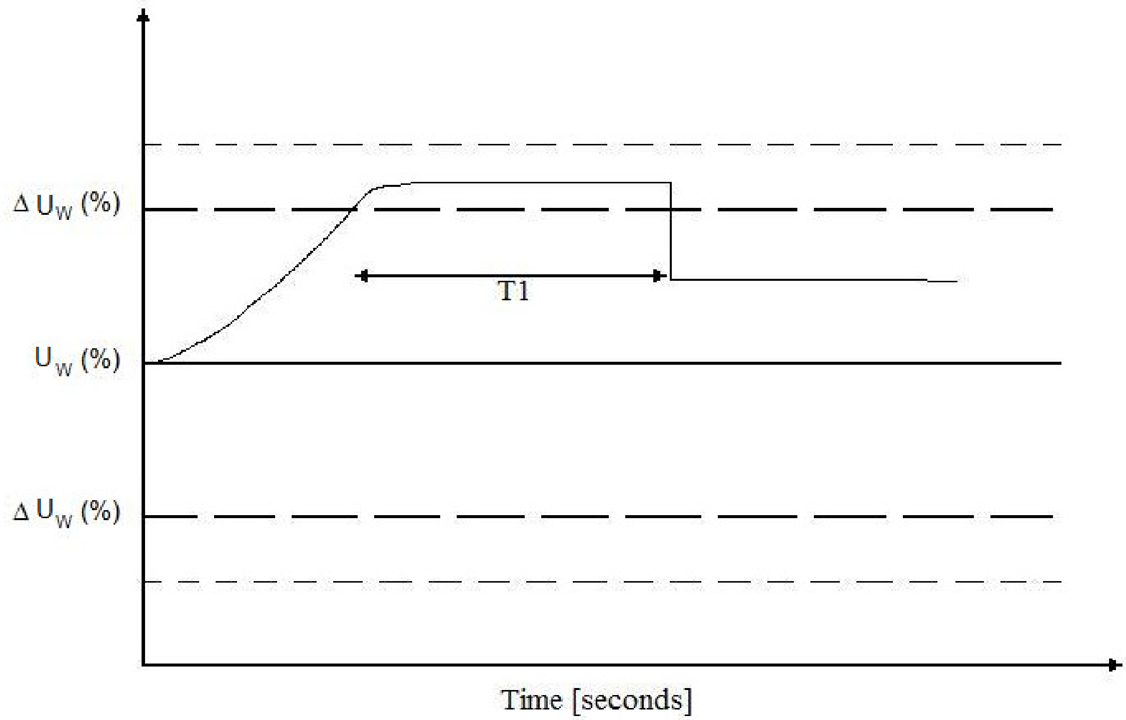

Figure 13: Voltage deviation that requires one tap change

The “Const” time program operates in a definite time for specific deviations from the set limits. There are two time settings, T1 and T2 that are used in this time program. Consider a case where the loading on the network increases gradually to a level where one tap change is required to return the voltage to within the set limits: in this case, the REG-D relay would issue a command to tap in time T1 as illustrated in Figure 13.

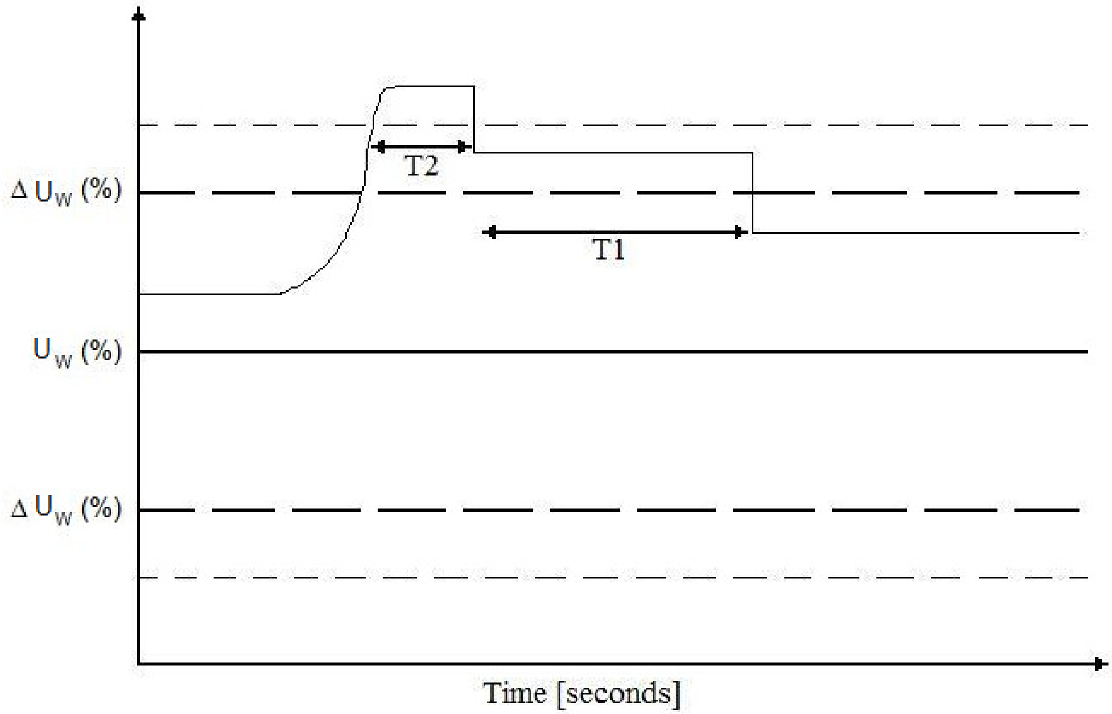

Figure 14: Voltage deviation that requires more than one tap change.

If the secondary voltage of a distribution transformer increases drastically to the extent to which more than one tap change is required to return the voltage to within the set limits then the initial tap changes would occur at intervals of time T2 seconds until a situation where one tap change would be sufficient to return the voltage to within the set limits; this last tap change would then occur after time T1 seconds as illustrated in Figure 14.

The optimal time behaviour of the regulator can be achieved by returning the voltage to within the set limits with the minimum number of tap changes, and, in such a way that large deviations from the set voltage should be rectified quicker than small deviations. The Integral time program attempts to achieve this by using an inverse definite minimum time characteristic which is defined by:

$$\Delta U_W \times t = const \tag{8}$$

Where:

$const = 0.1...30$

ΔU_W is the percentage deviation from the set voltage

t is the time delay

Note: The REG-D manufacturers adopt the terminology ΔU to represent a voltage deviation in actual units, and the terminology ΔU_W to represent a voltage deviation in percentage of the set point voltage. The same terminology is used here.

Implementing equation (8) will ensure that large deviations from the set voltage will be rectified quickly and small deviations will be rectified more slowly. A model of the abovementioned time programs was developed and included in the real-time model of the REG-D relay developed for this thesis. The real-time simulation model of these time programs is shown in Figure 15. In this real-time model of the time programs the user can choose which time program to use by changing the status of a switch in the Run Time interface. When the status of the switch is 1 the "Integrator" time program will be active and when the status of the switch is zero the "Const" time program will be active.

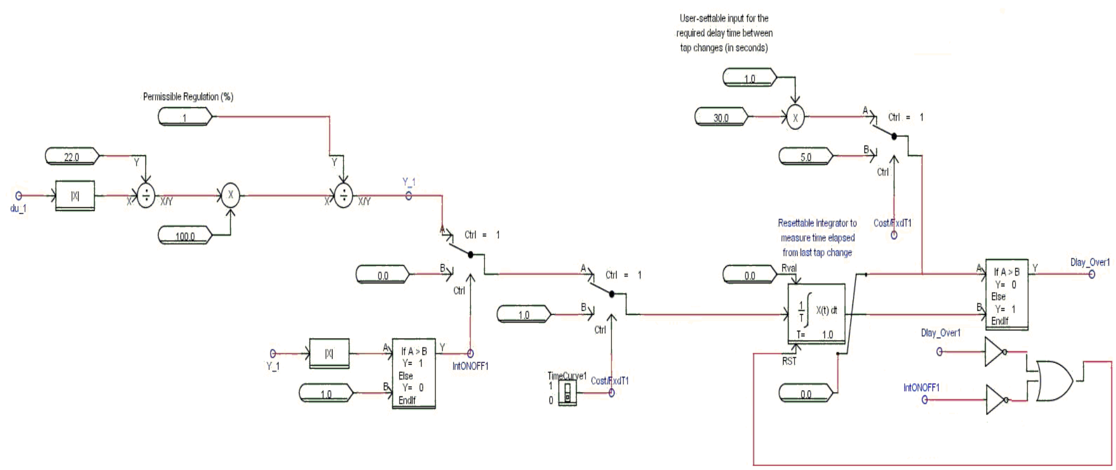

Figure 15: The real-time simulation model of the REG-D Time programs.

From the real-time simulation model shown in Figure 15 it can be seen that the permissible voltage regulation is a set point chosen by the user as a percentage of the set point voltage value. The voltage deviation ΔV in kV (denoted in Figure 15 as du_1) is an input to the Integrator time program which ensures that the time delay is dependent on the size of the voltage deviation. If the actual voltage deviation is less than the permissible voltage deviation the time program is deactivated. This is true despite which of the two time programs has been chosen by the user.

In this subsection the voltage regulating algorithm and the time programs available on the REG-D relay have been discussed. The discussions have shown that there are two settings that should be considered for the voltage regulating algorithm, namely, the set point voltage and the permissible voltage deviation. The set point voltage is determined by the secondary voltage of the transformer. The permissible voltage deviation setting must be chosen such that its value is greater than 60% of the percentage voltage change that is obtained from a single change in transformer tap position. This will ensure that the tap-changer is stable for all voltage deviations and that the tap-changer does not fluctuate around the set point voltage.

4.2.2 Circulating current regulating algorithm

Earlier it has been mentioned that when transformers are connected in parallel or in a meshed network topology, circulating reactive currents can flow between these transformers. The REG-D relay uses the Δcosφ algorithm for controlling circulating reactive currents between transformers that are tens of kilometers apart and where there is no communication link between the relays. In this subsection the real-time simulation model of the REGD-D's Δcosφ algorithm will be discussed in detail.

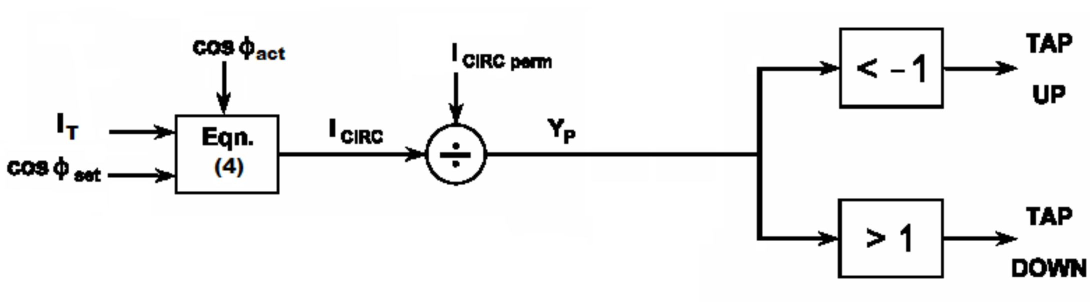

Figure 16: Circulating current regulation block diagram.

Figure 16 shows the block diagram of the Δcosφ algorithm. As it was explained in Chapter Two the REG-D relay measures the actual current that flows in the secondary side of the transformer as well the secondary voltage of the transformer. The relay circulating current algorithm computes the circulating current as shown in equation (4). The calculated circulating current is then normalised by dividing it by the permissible circulating current.

The circulating current that flows between the two transformers in parallel is limited by the impedance between the two transformers. It is recommended by [3] that the permissible circulating current should be:

$$I_{CIRCperm} > 0.6 \times (Ib^{**} - Ib^{*}) \qquad (9)$$

Where:

$I_{CIRCperm}$	is the permissible circulating current
Ib^{*}	is the reactive current measured when the transformers are at the same tap position
Ib^{**}	is the reactive current measured when the transformers are one tap position apart

The signal Y_P is the ratio between the circulating current that flows between the transformers and the permissible circulating current. When Y_P is less than negative one then the circulating current algorithm will issue a command to tap the transformer up and when the signal Y_P is greater than one the circulating current algorithm will issue a command to tap the transformer down.

Similarly to voltage regulation, there are limits that are set to the circulating current that may be allowed to flow. These limits are dependent on how much circulating current can be tolerated. For example, if the transformers in a distribution network are expected to carry close to full load current then it would be wise to limit the circulating currents to a minimum so as to ensure that the loading of the transformer is not exacerbated by the circulating reactive current. On the other hand, in cases where the transformers are expected to carry much less than full load current, then some circulating currents may be allowed to flow.

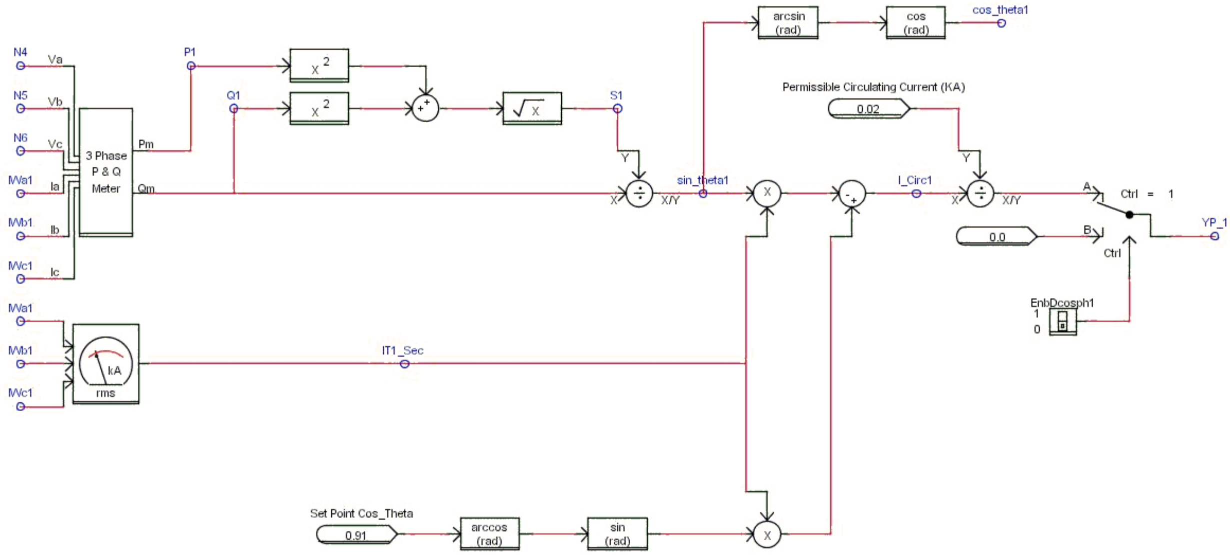

Figure 17: The real-time simulation model of the REG-D Δcosφ algorithm.

Figure 17 shows the real-time simulation model of the Δcosφ algorithm developed for this thesis. In Figure 17 it can be seen that the relay measures the three phase currents and voltages at the secondary terminals of the transformer. From the measured quantities the algorithm computes the measured power factor angle. The user defines the set point power factor angle. Using equation (4) the Δcosφ algorithm computes the circulating current.

The computed circulating current is then normalized by dividing it by the permissible circulating current. It should be noted that the permissible circulating current setting is also user defined. The normalized circulating current variable Y_P is the error signal output from the circulating current algorithm. The user is also able to enable and disable the circulating current algorithm by changing the status of a switch in the Run Time interface of the real time simulator when the simulation is running.

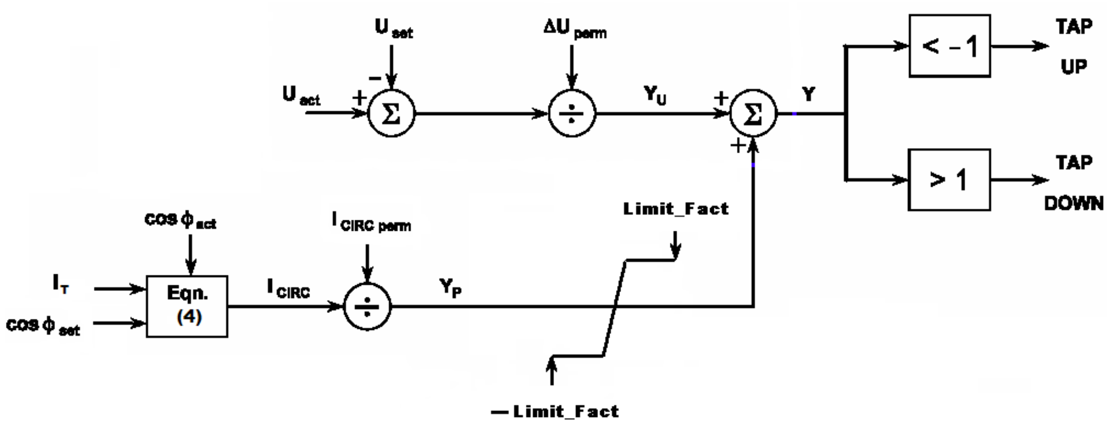

Figure 18: A block diagram of the combined voltage and circulating current algorithms.

The REG-D relay combines the voltage regulating algorithm and the circulating current algorithm by adding the error signals (Y_U and Y_P) from each algorithm to obtain a combined error signal Y, thus enabling the relay to regulate both quantities, as shown in Figure 18 above.

The REG-D relay is primarily a voltage regulating relay but it is also able to regulate circulating reactive currents. The user is able to prioritise which variable will have more influence on the combined error signal Y by setting the limitation factor applied to the circulating current control algorithm. Consider a case where voltage regulation is of high priority, the limitation factor will be set to a minimum which must nevertheless be higher than zero.

Figure 19 shows the full real time simulation model of the REG-D relay developed for the studies in this thesis. The real time model includes the facility to allow the user to switch to manual control of the transformer tap changer while the simulation is running (as it is possible on the actual REG-D relays); in manual control mode, the user is able to tap the transformer manually by using the push buttons in the Run Time interface. Also the user is able to view the variables from the simulation model of the REG-D in the Run Time interface during a simulation. The performance of the REG-D simulation model will be compared to that of an actual REG-D relay in the following section.

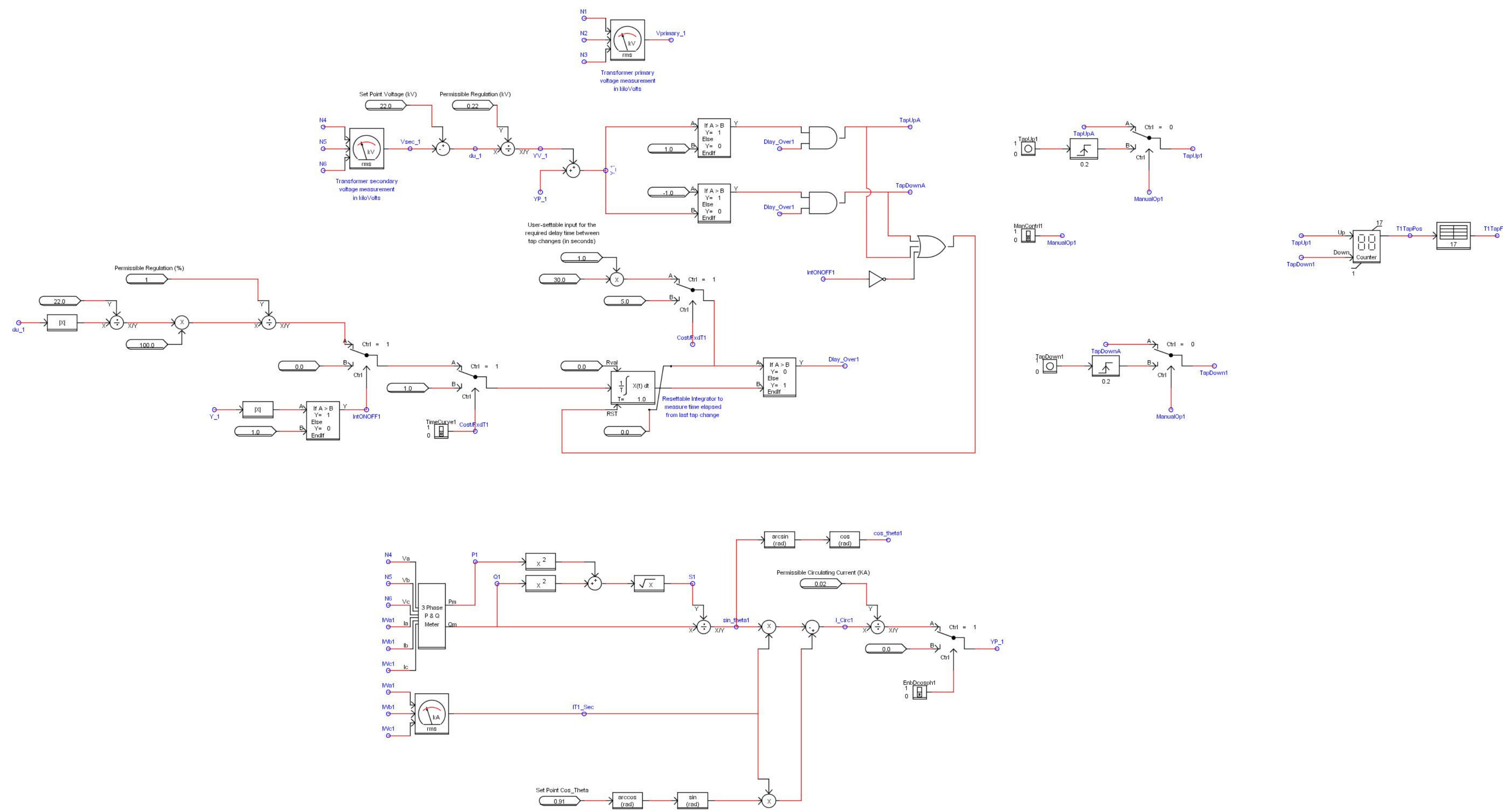

Figure 19: The real time simulation model of the `REG-D relay.

4.3 Real – time simulator testing of the REG-D algorithms

A simple two transformer study system was used to carry out tests to compare the performance of the simulation model of the REG-D relay against that of an actual REG-D relay. Two identical 88/22kV 20MVA transformers fed from the same ideal 88kV voltage source were modelled using a real–time digital simulator. The schematic diagram of the test arrangement is shown in Figure 20, which shows that the two transformers are modelled in the real time simulator with an actual REG-D relay connected hardware-in-loop with transformer T2. The analogue measurements of the secondary voltages of transformer T2 are fed to the physical REG-D relay externally to the simulator via an amplifier. The relay's outputs for raising and lowering the transformer's tap position are fed back to the simulation model via a TTL digital input ports on the simulator. The detailed implementation of this block diagram on the real time simulator is shown in Figure A1 in Appendix A.

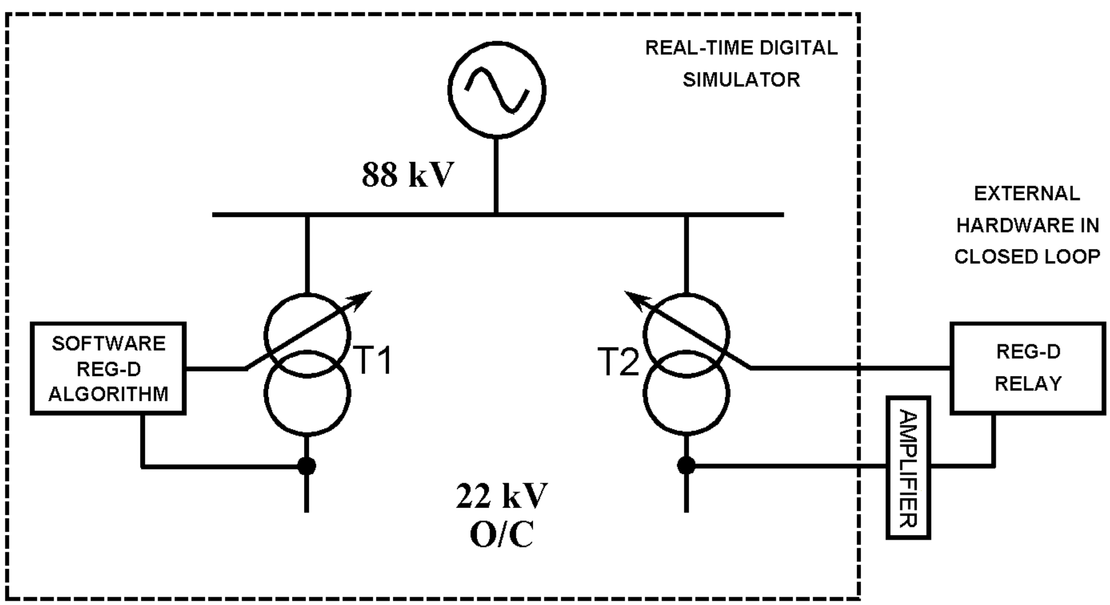

Figure 20: Real-time simulator testing of the REG – D relay voltage regulating algorithm

The real-time model of the REG-D relay described previously in this chapter was used to control the secondary voltages of transformer T1. Both transformers' secondaries were left open circuit in the real-time model. The performance of both relays (hardware REG-D and simulated REG-D) was compared in response to disturbances to the common primary voltage feeding their respective transformers, with both REG-Ds given identical settings.

In order to compare the accuracy of the inverse time characteristic of the simulation model of the REG-D and its ability to regulate the transformer secondary voltage in the same manner as the hardware REG-D relay, a number of voltage regulation tests were performed. The initial test that was performed was that of a step reduction of the primary voltage source to 94% of its nominal value, forcing the secondary voltage of both transformers initially to drop by the same magnitude of 6%.

Both the simulation model of the REG-D relay and the actual hardware relay were allowed to regulate the secondary voltages of their transformers in response to this deliberate primary voltage reduction. Figure 21 below shows the response of the simulation model of the REG-D relay and that of the hardware REG-D relay.

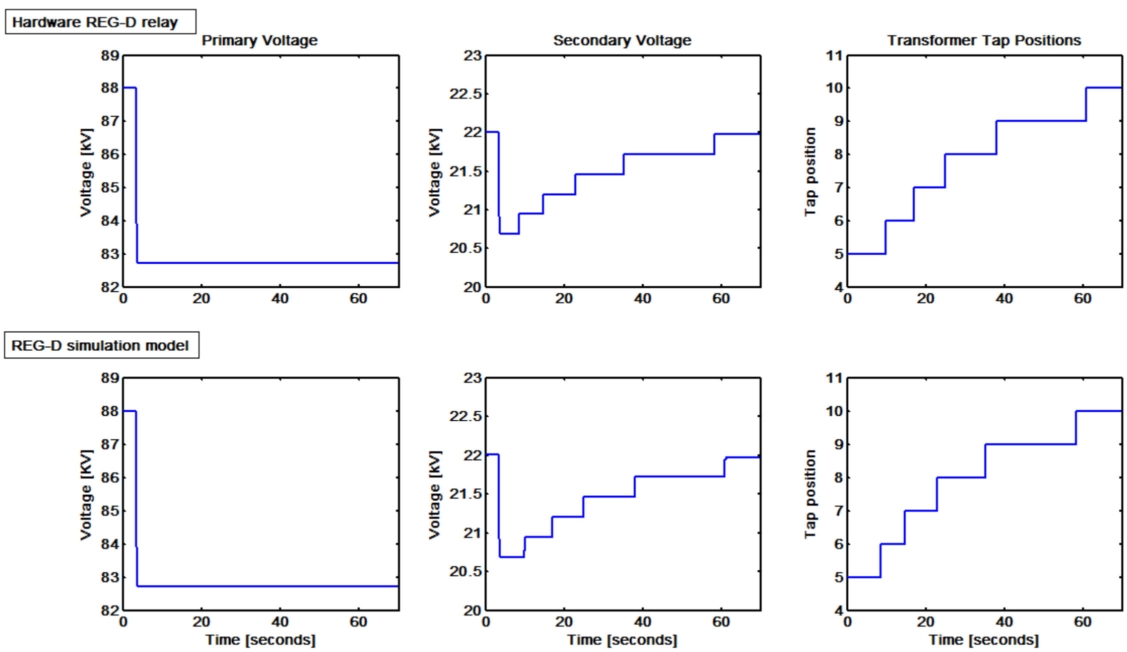

Figure 21: Comparison of simulation vs. hardware REG-D voltage regulation algorithms in response to a step change in transformer primary voltage.

From Figure 21 it is evident that both the simulation model and hardware relay returned the secondary voltages of their transformers to nominal voltage within the same period and with the same number of tap changes.

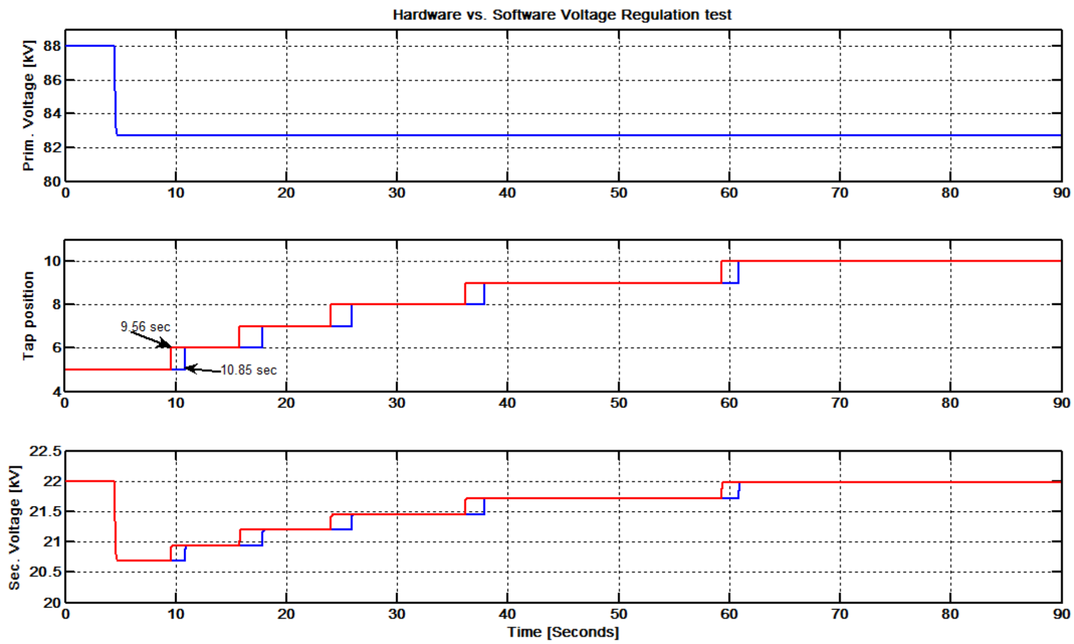

Figure 22: Superimposed plot of the tap positions and secondary voltages of transformers T1 (red) and T2 (blue), from the test result shown in Figure 21.

According to [3] the tolerance of the operating times of the REG-D relay is 2 seconds. Figure 22 shows the transformer T1 and T2 tap positions and their secondary voltages from the test in Figure 21 now plotted on the same axis. The tap position and secondary voltage of transformer T1 is in red and that of transformer T2 is shown in blue. From Figure 22 it can be seen that the time difference between the tap changes of the transformer controlled by the actual REG-D relay and those of the transformer that is controlled by the REG-D simulation model are within the tolerance of the operating times of the practical relay in all cases. This trend is also evident in the secondary voltages of the transformers as shown in Figure 22 where the initial tap change of the transformer T1 occurs at time t = 9.56 seconds and that of transformer T2 occurs at time t = 10.85 seconds.

In order to verify the simulation model of the REG-D's circulating current regulation algorithm a second test was carried out. Similarly to the test of the voltage regulation algorithm, two identical 88/22kV 20MVA transformers fed from the same ideal 88kV voltage source were modelled using a real – time digital simulator. For this test the two transformers were connected to a common constant-PQ type load L as shown in Figure 23.

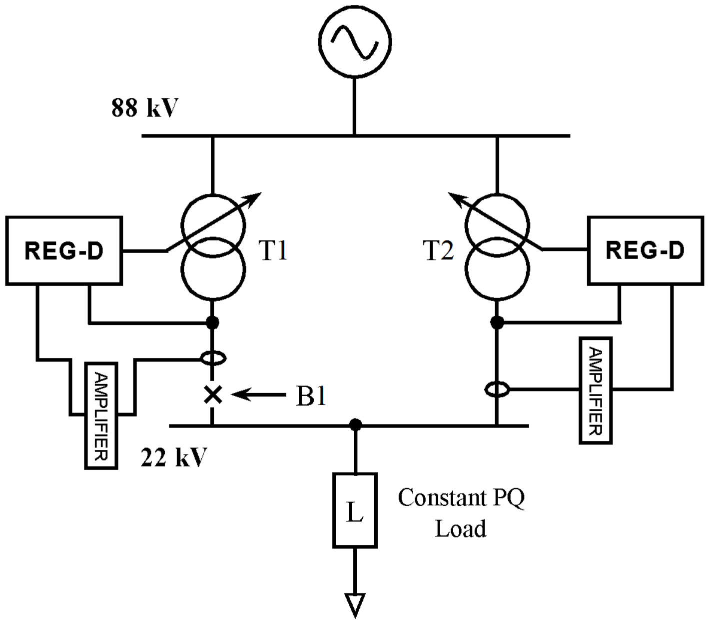

Figure 23: Real-time simulator testing of the circulating current regulation algorithm.

This test had two parts. In the first part the two transformers in the real-time model were both controlled in closed-loop by hardware REG-Ds external to the simulator. In the second part of this test, both of the transformers were controlled by a simulation model of the REG-D relay. In both parts of the test transformer T1 was temporarily disconnected from the network by opening breaker B1. While breaker B1 is open, the entire load at L is carried by transformer T2 alone, and thus transformer T2's regulator has to increase its tap position several times, to a higher value, in order to return the single, heavily-loaded transformer's secondary voltage to an acceptable value. In each part of the test, transformer T2's regulator was allowed to finish increasing its tap position to this new, higher value, before transformer T1 was then returned to service at its *nominal tap position*. This test was carried out to replicate a typical set of circumstances that can give rise to circulating current in practice, and then to examine the performance of the REG-D algorithms (simulated and practical) in response to these currents. In both parts of the test the response of the REG-Ds to this disconnection and reconnection of transformer T1 was measured with the $\Delta\cos\varphi$ algorithm enabled, then disabled.

When transformer T1 is returned to service by closing circuit breaker B1, circulating reactive current initially flows between the transformers. Since transformer T1 is at nominal tap position (tap position five) when it is reconnected, and transformer T2 is at a higher tap position (position thirteen in this case), the internal voltage of transformer T2 is higher than that of transformer T1 resulting in circulating reactive current flowing from transformer T2 to transformer T1.

The circulating current that flows into transformer T1 lifts the secondary voltage of transformer T1 to nominal voltage as shown in Figure 24, therefore transformer T1 does not need to make any tap changes to regulate its secondary voltage. From Figure 24 it can be seen that transformer T2 carries a large lagging reactive load while transformer T1 carries a smaller, but leading reactive power load even though the two transformers share equally the active power loading. Transformer T2 is more heavily loaded than transformer T1. This holds for both (simulated and hardware REG-D) parts of the test.

In Appendix C hand calculations are presented. These calculations were done in order to cross check the active and reactive power loadings of the two transformers obtained in Figure 24, when transformer T2 is at tap position 13 and transformer T1 is at nominal tap position. The assumptions that were made in the calculations in Appendix C are that the internal voltages of the transformers are in phase and that the leakage reactance of the transformers does not change with each tap change. Also, it was assumed that the load L is a fixed-impedance load that gives 40 MVA at a power factor of 0.9 when nominal voltage is applied and that the load consists of a parallel combination of the load resistance and load reactance. The calculation method used in Appendix C is somewhat simplified compared to the real-time models used to generate the results in Figure 24, but these hand calculations are useful to check the basic correctness of the predicted reactive loadings shown in Figure 24 under circulating current conditions.

The simplified hand calculations in Appendix C predict that for this particular skew in tap positions between the two transformers, transformer T1 will have a small leading reactive power loading of 1.208MVars and transformer T2 will have a significantly higher, and lagging reactive power loading of 18.75MVars. The results of the simulation studies shown in Figure 24 are thus in broad agreement with the approximate, hand-calculated reactive power loadings on the transformers carried out in Appendix C. This is true for the results obtained when the simulation model of the REG-D relay was allowed to control the transformers, as well as for the results obtained when the hardware relays were controlling the two transformers in the simple distribution network.

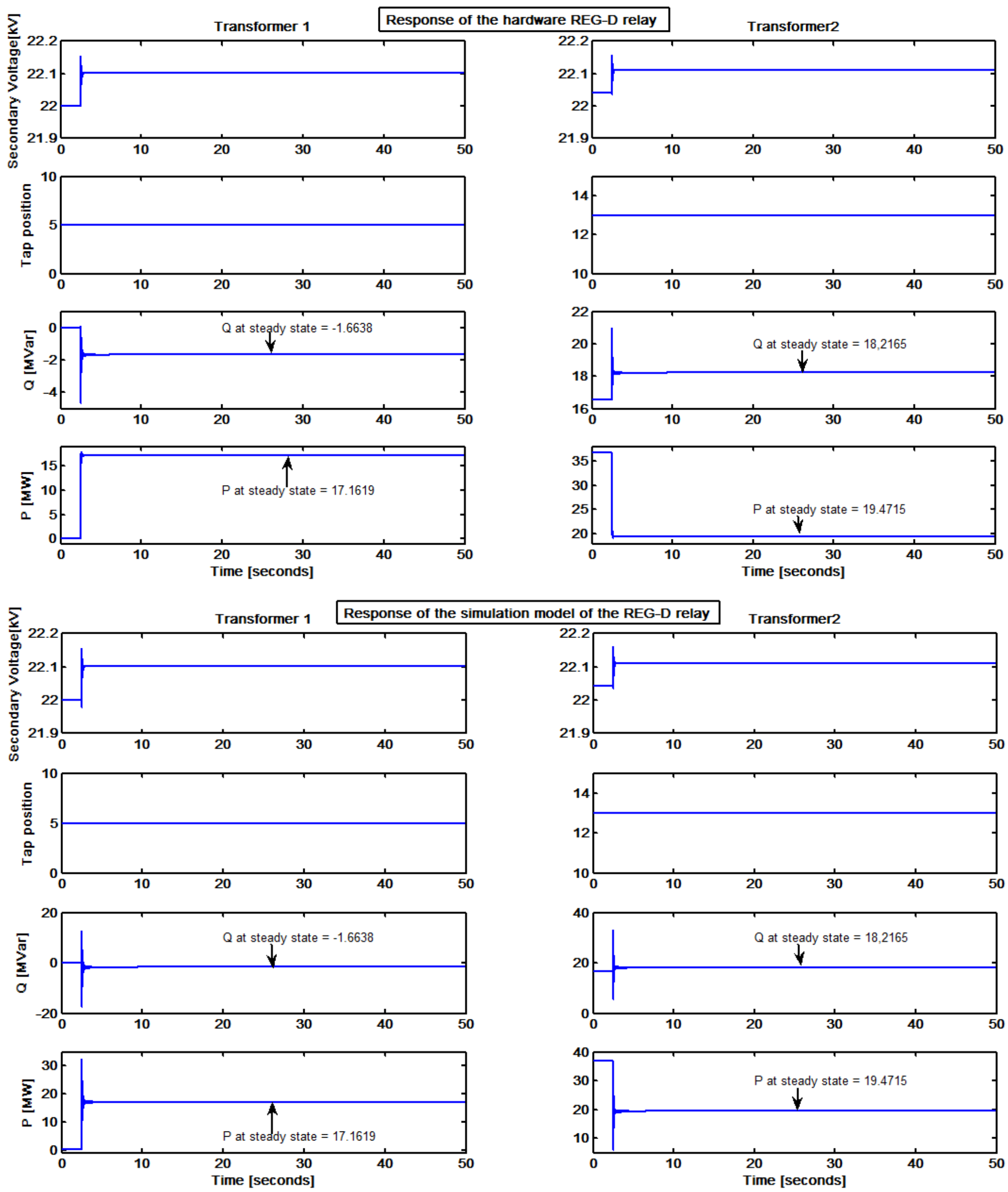

Figure 24: Comparison of simulated vs. actual (hardware) REG-D algorithms in response to re-connection of transformer T1: Δcosφ control disabled.

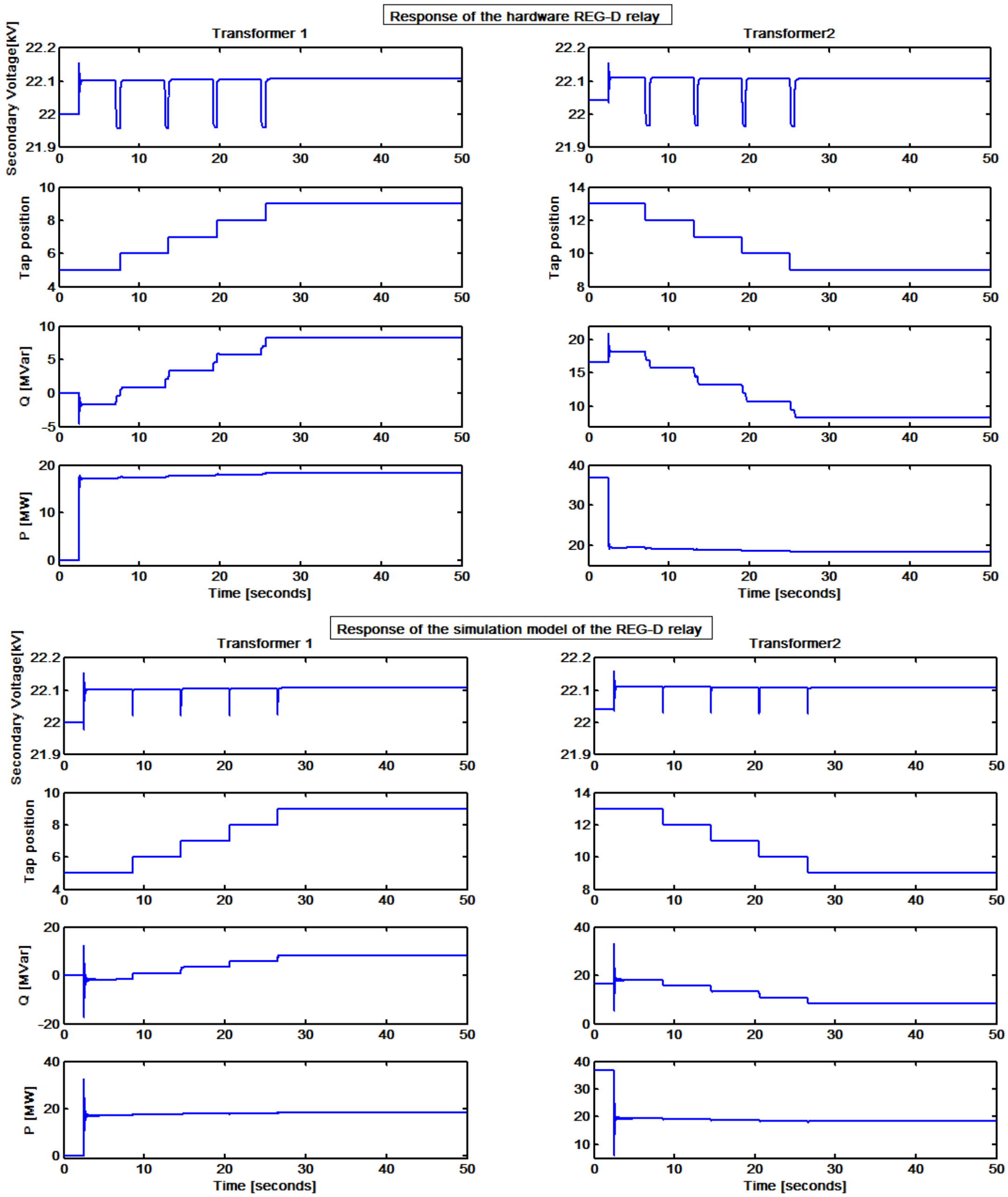

Figure 25: Comparison of simulated vs. actual (hardware) REG-D algorithms in response to re-connection of transformer T1: Δcosφ control enabled.

The test was then carried out with the Δcosφ algorithm enabled and Figure 25 shows that the simulation model of the REG-D relays and the actual hardware relays are able to regulate both the circulating current and the transformer's secondary voltages. When transformer T1 is returned to service its secondary voltage is at nominal tap position but the transformer is forced to tap up in order to reduce the circulating current. With each tapping of transformer T1, transformer T2 taps down also to minimize the circulating current. The two transformers end up at the same position, sharing both the active and reactive power burden of the load L.

4.4 Testing the effect of Limitation Factor setting on the performance of the REG-D relay

When the Δcosφ algorithm is enabled the user acquires access to a Limitation Factor setting. This Limitation Factor setting is a limit placed on the size of the output signal Y_P that is output from the Δcosφ algorithm before being combined with the voltage regulation error Y_U to form a single regulator error Y (see Fig. 18). The Limitation Factor setting is thus set by the user in order to determine the relative influence of the Δcosφ algorithm's output Y_P (representing the normalised circulating current) on the final control error signal Y. This setting thus enables the user to prioritise which of the two variables (secondary voltage or circulating current) will have more influence on the combined error signal Y.

Since the Limitation Factor setting limits the influence of the error signal from the Δcosφ algorithm (Y_P) on the combined error signal Y, when the Limitation Factor setting is set to zero then the voltage error signal takes priority. It should be noted that when the Δcosφ algorithm is enabled the Limitation Factor setting can only be set to a minimum of 2. Figure 26 below shows the effect of the Limitation Factor setting on the performance of the REG-D relay.

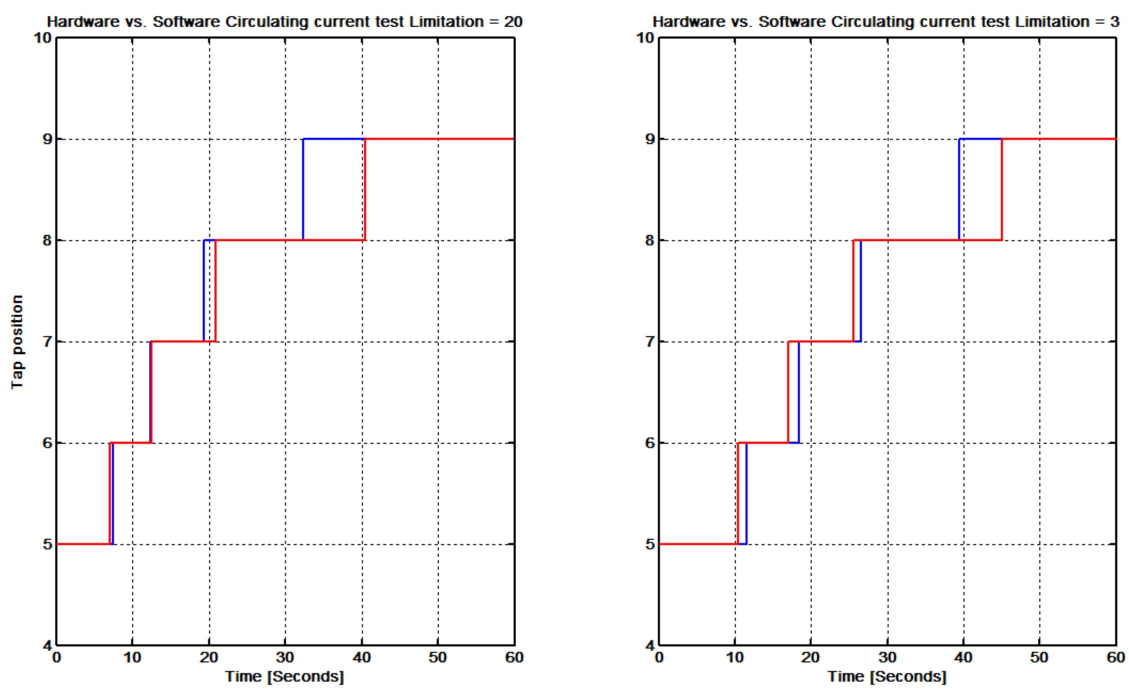

Figure 26: The effect of the Limitation Factor setting on the performance of the REG-D relay.

Figure 26 shows the results of two tests that were carried out in order to test the effect of the Limitation Factor setting on the performance of the REG-D relay. During these two tests the transformers were configured as shown in Figure 23, where transformer T1 was controlled by a simulation model of the REG-D relay internal to the RTDS. Transformer T2 was controlled by an actual hardware REG-D relay external to the RTDS. The load L was connected to the network whilst the simulation model of the REG-D relay and the hardware REG-D relay were on manual mode to prevent them from changing the tap positions of the two transformers.

The simulation model of the REG-D relay and the hardware REG-D relay were then allowed to regulate the transformers' secondary voltages as well as to control the circulating current that may flow between the transformers by toggling their mode of operation to automatic. For the first test the Limitation Factor setting was set to 20 and for the second test the Limitation Factor setting was set to 3. Figure 26 shows that when the Limitation Factor setting is set very high the initial tap changes of the transformers were quicker than the tap changes for a condition where the Limitation Factor setting was set very low. Figure 26 shows that a user can prioritize between the voltage regulating algorithm and the $\Delta\cos\varphi$ algorithm by choosing a high Limitation Factor setting or a low Limitation Factor setting. It should be noted that as shown in Figure 18 the Limitation Factor setting limits the contribution of the error signal from the $\Delta\cos\varphi$ algorithm to the combined error signal.

4.5 Conclusion

In this Chapter the REG-D voltage regulating algorithm, circulating current algorithm and the time programs were modeled in detail using a real-time simulator. The performance of the simulation model of the REG-D's voltage regulation and circulating current control algorithms was compared to that of the actual REG-D relay. It was found that the simulation model of the REG-D is able to regulate both voltage and circulating current. The response of the simulation model agreed with that of the actual REG-D to within acceptable tolerances. The simulation model may be used in other packages to test the performance of the relay under realistic distribution network conditions.

In this Chapter, the performance of the voltage regulation and circulating current control algorithms of the REG-D was tested in the simplest possible network that comprised two transformers connected to the same bus, supplying a constant PQ load since the focus has been on developing a model of, and on understanding the relay itself. In Chapter Five, it will be investigated how the REG-D relay and its simulation model perform in a realistic distribution network. The performance of the simulation model of the REG-D relay will again be compared to that of the actual hardware relay.

CHAPTER FIVE

Testing the Performance of the $\Delta\cos\varphi$ Algorithm in a Realistic Distribution Network

5.1 Introduction

Previously the performance of the simulation model of the REG-D relay was compared to the performance of the hardware REG-D relays using a simple two transformer network, where the transformers are fed from the same source and the transformers are connected to the same bus at their secondary terminals. The simple two transformer system was used to demonstrate that the response of the real-time simulation model of the REG-D relay ties up with that of the hardware REG-D relay to within acceptable tolerances.

It has been discussed in Chapter Two that there are different algorithms that are available in the market for regulating transformer secondary voltages and circulating current between parallel transformers. A number of these algorithms are limited by the fact that they require a communication link between the relays in order to regulate both circulating current and secondary voltages of the transformers.

The Limiting Factor setting of these algorithms implies that these relays would be restricted in controlling circulating currents and secondary voltages of transformers that are tens of kilometers apart in a meshed distribution network. It would be uneconomical to install communication links between the relays. The REG-D circulating current algorithm does not require a communication link between transformers. In Chapter Four it was shown that the algorithm is able to regulate both circulating current and transformer secondary voltages in a two transformer network without any communication link between the relays.

In Chapter Five the performance of the real-time simulation model of the REG-D relay in a realistic network will be tested. The settings of the $\Delta\cos\varphi$ algorithm will be designed using the simulation model of the REG-D relay. Circulating currents will be forced to flow between the transformers by changing the network configuration and the simulation models of the REG-D relay will be allowed to regulate these circulating currents. The performance of the simulation models of the REG-D relay will then be compared to that of the actual relays.

5.2 The Network Under Study

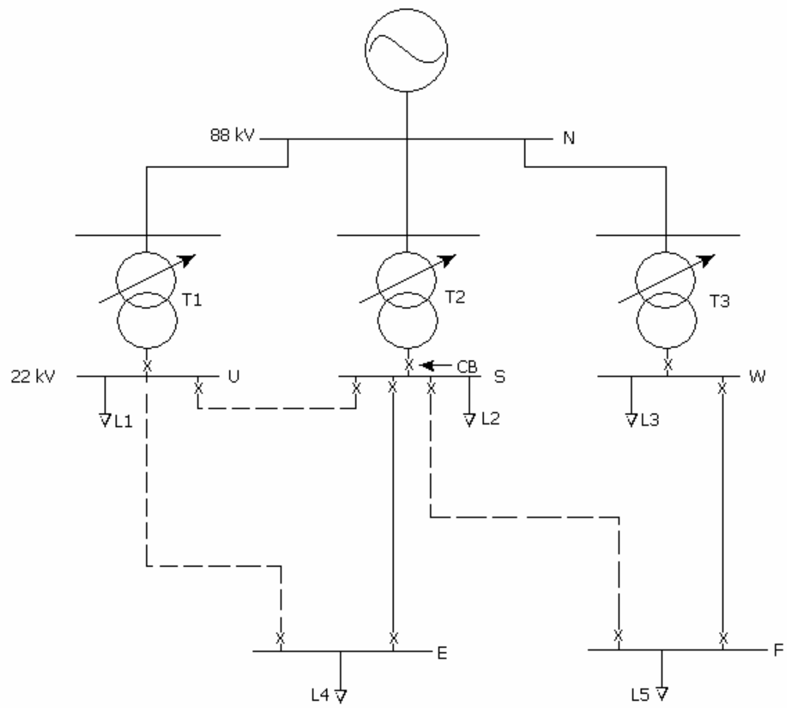

Figure 27: The single-line diagram of the Eskom Upper South Coast Distribution Network [7].

The distribution network that was used to test the performance of the REG-D relay under realistic conditions is that of Eskom in the upper south coast region of KwaZulu-Natal as shown in Figure 27. The network is supplied from substation N at 88 kV via three 88 kV feeders to three separate substations U, S and W. Each of the three substations has a 20 MVA, 88 kV on-load tap-changing transformer and they each supply local loads L1, L2, L3 at 22 kV. The three substations U, S and W also supply a switching station E and a substation F via 22 kV feeders, which in turn supply local loads L4 and L5 respectively.

The network has five feeders interconnecting the four substations U, S, W, and F as well as the switching station E. These interconnecting feeders would allow the network to operate in a meshed topology but under normal operating conditions switching station E is supplied only from substation S and substation F is supplied only from substation W, in order to avoid the circulating currents that might otherwise flow between the three transformers T1, T2 and T3. Under normal operating conditions the feeders that are drawn with dashed lines do not carry any network load. These feeders are only used for contingencies. The tests in this chapter will be performed whilst the network is in a meshed network topology.

Initially the relay settings will be designed and tested using the simulation model of the REG-D relay. Later these settings will be implemented in actual hardware relays for hardware-in-loop real-time simulator testing. The response of the real-time simulation model of the REG-D will then be compared to the response of the actual REG-D hardware.

5.3 Design and testing of the settings of the Δcosφ algorithm

5.3.1 The $\cos\varphi_{set}$ Setting

The design of the settings for the Δcosφ algorithm will be discussed in this section. In order to obtain network $\cos\varphi_{set}$ settings, the real-time model of the meshed network in Figure 27 was allowed to reach quasi steady state with the tap changing relays on manual operating mode, and with the network itself at a fixed operating point (ie. constant values of loads L_1 to L_5). The network transformers were at nominal tap position (tap position 5). The power factor angle at each of the transformers was obtained from the internal variables of the real-time model of the REG-D relay operating on that transformer under these steady state conditions, and each such value was used to determine the $\cos\varphi_{set}$ setting for that REG-D relay.

Tests were conducted to examine the performance of the real-time model of the REG-D relay with the Δcosφ algorithm disabled and later enabled when the relays are controlling tap changing transformers in the study system shown in Figure 27. To perform these tests the distribution network was subjected to topological changes designed to disturb it from equilibrium so that the response of the REG-D relay could be examined. A similar study was conducted in [7] and in that study the permissible circulating current was set to 20 A, a decision based primarily on engineering judgement.

Similarly, for the initial tests considered in this chapter of the thesis, the permissible circulating current setting was also set to 20A. The motivation for this particular value of 20 A as the permissible circulating current setting was purely as a starting point in order to be able to confirm the results obtained in [7] by repeating the same assumptions made in that study. It should be noted that the question of how to design properly the permissible circulating current settings for the particular study system in Fig. 27 is considered in more detail later in the thesis.

With the Δcosφ algorithm disabled the transformer breaker at substation S (circuit breaker CB in Figure 27) was opened and the transformer T2 was manually tapped down to nominal tap position. Transformers T1 and T3 were allowed to automatically tap until their secondary voltages were within their permissible regulative deviations. After the transformers had completed tapping to their respective post disturbance steady state tap positions, transformer T2 was reconnected to the network by closing the transformer breaker at substation S. The response of the relays to the second of these disturbances (ie. reconnection of transformer T2) is shown in Figure 28.

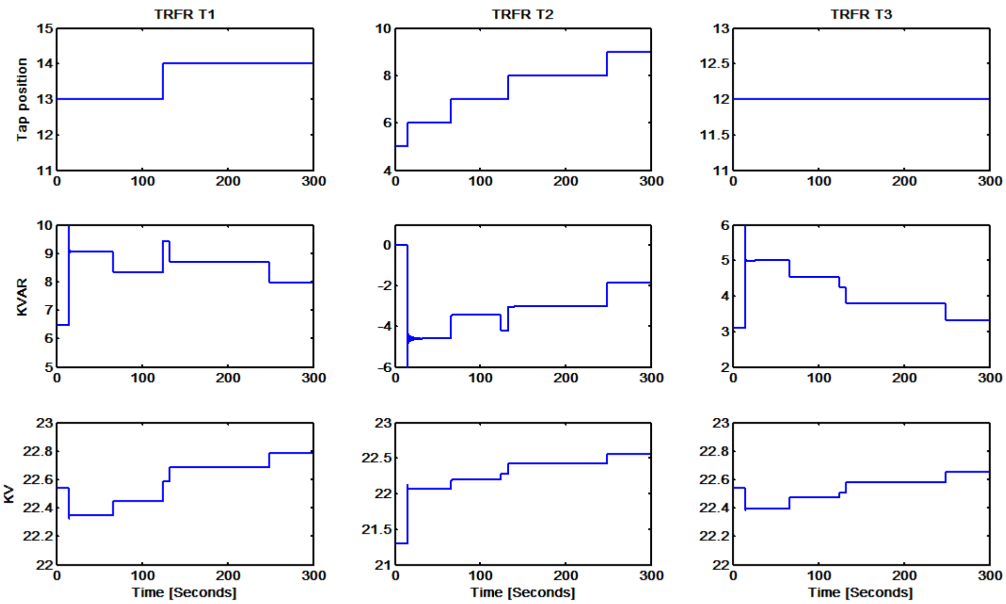

Figure 28: The response of the system following the reconnection of T2. (Δcosφ algorithm disabled)

From Figure 28 it can be seen that even though the regulator at transformer T2 raises its tap position from nominal after it is reconnected, the three transformers remain at considerably different tap positions even once steady state has been reached. The circulating current that flows between the transformers is as a result of these differences in the tap positions between them, but the amplitude of the circulating currents (and hence the reactive loading on the individual transformers) is also influenced by the impedance between particular pairs of transformers. In the system of Figure 27, the impedance presented to circulating currents between transformers T1 and T2 is significantly lower (because of the dominant effect of the short line directly connecting substations U and S) than the impedance presented to circulating currents between transformers T2 and T3 (which is made up of two longer lines connecting substations S and W, via the remote substation at F).

Therefore in the results of Figure 28, when transformer T2 is initially brought back on line at substation S at a lower tap position than the two transformers at U and W, there is a considerably larger lagging reactive power burden placed on transformer T1 than on transformer T3, even though they are each initially at similar elevated tap positions relative to T2. In other words, there is inflow of circulating reactive current from both transformers T1 and T3 into the reconnected transformer T2, but the amplitude of the circulating current from transformer T1 (and hence the lagging reactive loading on T1) is considerably larger than that from T3.

The fact that the circulating current direction is *into* transformer T2 can be deduced from Figure 28 by the negative (leading) reactive power that is measured at the output of this transformer when it is reconnected, despite the actual loads in the system all having lagging power factors. Furthermore, it is because of this inflow of circulating current from transformers T1 and T3, that transformer T2 does not have to tap up to the same position as transformers T1 and T3 in order to restore its secondary voltage to the required set-point value; consequently, a large degree of reactive loading on the three transformers in Figure 28 is observed even after transformer T2 has completed its tap changes. In other words, the restoration of transformer T2's secondary voltage has been achieved in large part because of unwarranted inflow of circulating reactive current from transformers T1 and T3 instead of by transformer T2 being forced to tap all the way up to the same tap position as T1 and T3.

Figure 29 shows the response of the relays to the reconnection of transformer T2 with the $\Delta\cos\varphi$ algorithm now enabled. From Figure 29, it can be seen that with the $\Delta\cos\varphi$ algorithm enabled, each of the transformers T1, T2 and T3 reach the same final tap positions, such that no circulating currents flow between transformers once their regulators have reached steady state after the change in network topology. Consequently, in the post disturbance network there is no transformer that now has a very high reactive loading relative to other transformers. The reactive loading of each transformer is now dependent on the network configuration as well as on the network loads and not on any circulating current flowing between the transformers due to them being at different tap positions.

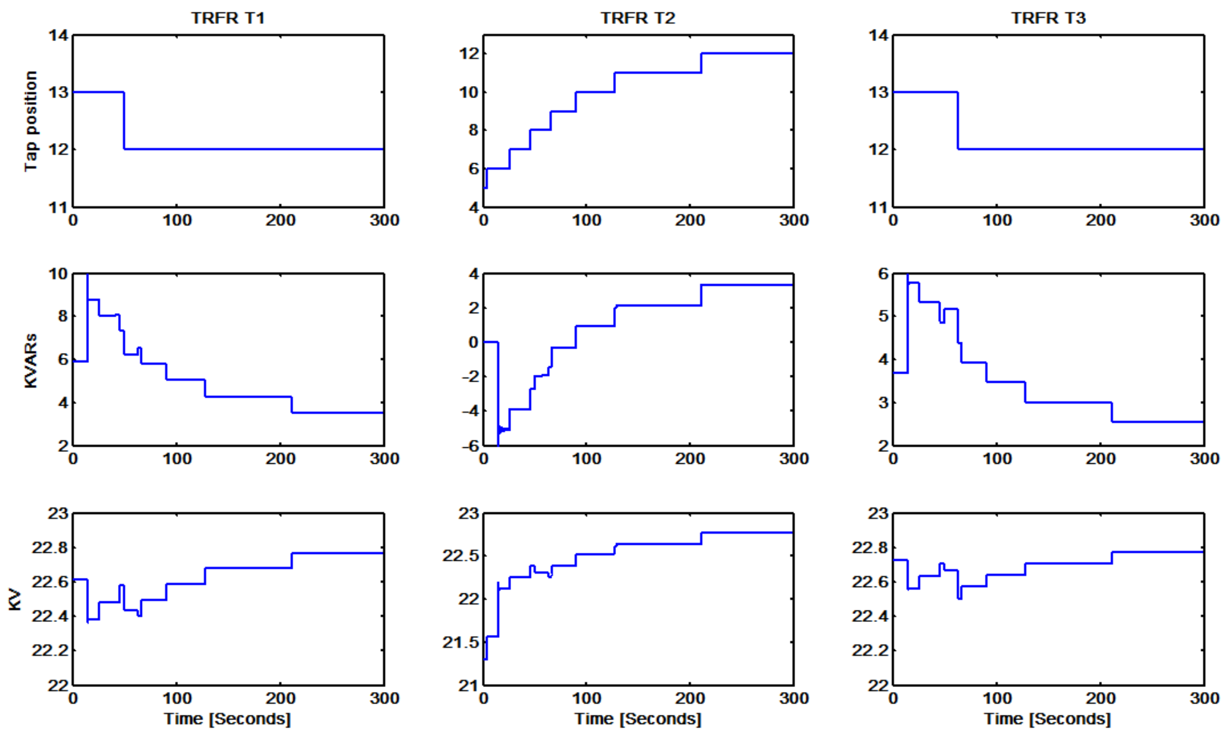

Figure 29: The response of the system following the reconnection of T2. (Δcosφ algorithm enabled)

5.3.2 The Limitation Factor Setting

As described in section 4.2.2, a Limitation Factor is applied on the output error Y_P of the circulating current regulation algorithm before this error Y_P is added to the error Y_U from the voltage regulation algorithm in the REG-D. This Limitation Factor allows the user to prioritise the relative influence of the two error signals Y_U and Y_P under transient disturbance conditions. The Limitation Factor is a user setting entered as a ratio of the measured circulating current to the permissible circulating current and its value must be greater than zero.

$$Limitation \quad Factor = \frac{I_{circ}}{I_{circ\_perm}} \tag{10}$$

In order to understand the effect of the Limitation Factor on the performance of the REG-D, the test shown in Figure 29 (with the Δcosφ algorithm enabled) was repeated for three different settings of Limitation Factor at all three REG-Ds, with the results shown in Figure 30.

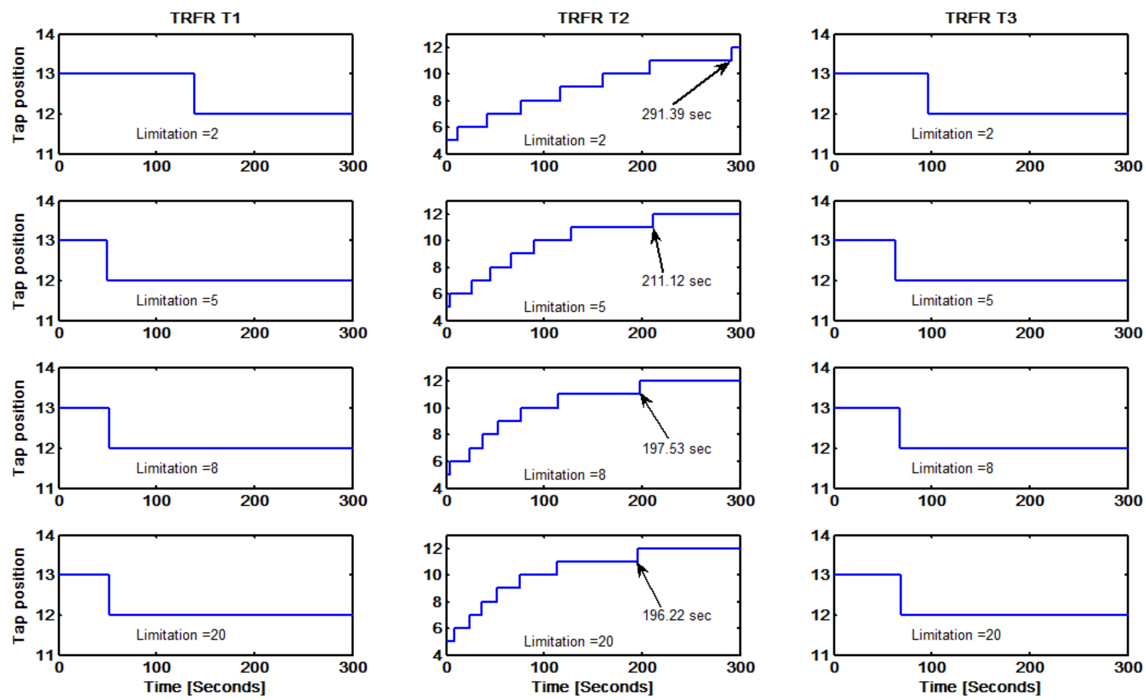

Figure 30: The response of the system following the reconnection of T2. (Δcosφ algorithm enabled and different Limitation Factor settings)

Figure 30 shows the effect of the Limitation Factor setting on the response of the system after transformer T2 has been reconnected to the network at nominal tap position. From the figure it can be seen that when the Limitation Factor is set to be the smallest value of 2 then the transformers' responses to the change in the network configuration are slow because the contribution of the Δcosφ algorithm's error Y_P to the combined error signal Y is limited to 2. In Figure 30 it can be seen that the last tap change that is performed by transformer T2 when the Limitation Factor setting is set to 2 occurs at time t = 291.39 seconds.

Similarly when the Limitation Factor setting is set to its maximum value of 20, then the Δcosφ algorithm has a greater influence on the combined error signal Y and thus the transformers respond more quickly to the circulating currents brought about by the same change in network configuration. Again, it can be seen Figure 30 that the last tap change performed by transformer T2 when the Limitation Factor setting is set to 20 occurs at time t = 196.22 seconds; this is considerably quicker than the case when the Limitation Factor setting was set to 2. Figure D1 in Appendix D shows further comparative analysis of these results from Figure 30, in which the responses of the system for two particular Limitation Factor settings (Limitation Factor settings of 2 and 5 from Figure 30) are replotted on the same axes.

It is important to note that for the different Limitation Factor settings the transformers always reach the same final tap positions. The Limitation Factor setting does not affect steady state regulation of either circulating current or secondary voltages, but simply which of the two regulative deviations takes priority during disturbances that result in large such deviations.

5.3.3 The Permissible Circulating Current Setting.

In the previous tests the permissible circulating current setting was set to 20 A, a setting that was initially used in [7] and based on engineering judgement rather than formal calculation. In order to determine the permissible circulating current setting more formally, according to the method described in [3], the transformers in the network need to be at the same tap position to ensure that the transformers have approximately equal secondary voltages; the transformers are then individually tapped up and down by one position, whilst measuring the reactive current that flows with each single change in tap position. The setting of the permissible circulating reactive current is then determined based on the measured currents during the test by means of equation (9) in Chapter Three.

In order to determine the setting for the permissible circulating current for transformer T1, all of the transformers were tapped to nominal position. The circulating current that was measured in each transformer was then denoted as Ib^{**} for that particular transformer. Then transformer T1 was tapped one tap position higher than transformers T2 and T3 and thereafter it was tapped one tap position lower than these two transformers. The average of the two measured circulating currents was denoted as Ib^{*} for transformer T1. Using equation 9 the setting of the permissible circulating current for each transformer was then determined from the measured values of Ib^{**} and Ib^{*}.

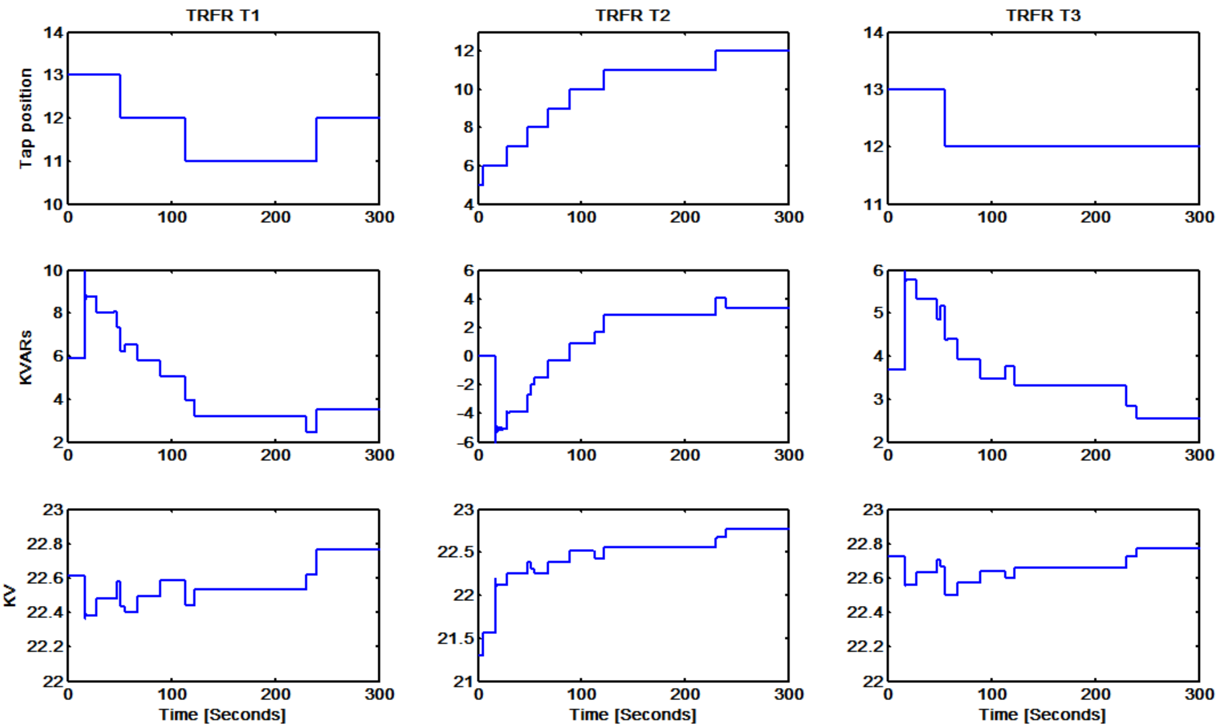

Figure 31: The response of the system following the reconnection of T2. (Δcosφ algorithm enabled and with properly designed permissible circulating reactive current settings).

Figure 31 shows the response of the system following the reconnection of T2 with the regulators having properly designed network $\cos\varphi_{set}$, I_{circ_perm} and Limitation Factor settings; these settings are shown in Appendix B. From Figure 31 it can be seen that when the Δcosφ algorithm is enabled the transformers tap to the same tap position thereby sharing the load equally. These settings were designed and tested using the simulation model of the REG-D relay. The response of the relays in regulating the circulating current that flows between the transformers was as desired as the transformers end up at the same tap position. Also the ability of the relays to regulate secondary voltages of the transformers was not affected since it can be seen that the secondary voltages of the transformers are within acceptable limits.

The designed settings shown in Table B.2 and B.3 were then applied to the actual REG-D relays. The relays were connected hardware-in-loop with the real-time model of the study system on the RTDS, in order to test the performance of the actual relays when the designed settings are used. In this test transformer T2 was again disconnected from the network and manually tapped to its nominal tap position. Transformers T1 and T3 were allowed to tap up until the network reached a new steady state operating condition. Transformer T2 was then returned to service by reconnecting it to the network and the response of the system was recorded.

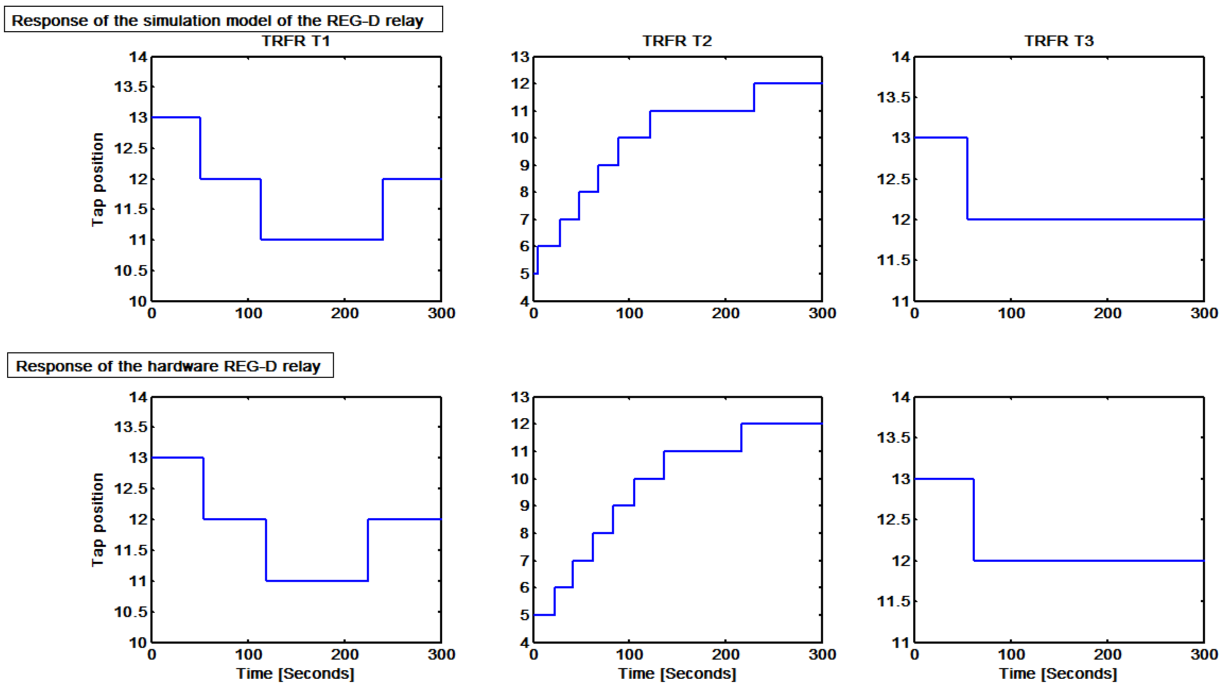

Figure 32: The response of the hardware-in-loop relays and the real-time relay models following the reconnection of transformer T2 to the network at nominal tap position.

Figure 32 shows that the hardware-in-loop REG-D relays respond in the same manner as that of the real-time models of the REG-D algorithms. All of the network transformers tap to the same tap position and the times to tap are within acceptable tolerances in each case.

5.4 Conclusion

In this chapter the settings of the $\Delta\cos\varphi$ algorithm were designed and tested using the real-time simulation model of the REG-D relay described in Chapter Three. The real-time model of the REG-D was able to regulate the circulating currents that flowed between the transformers of a representative study system after one of the transformers of this system was reconnected to the network at a different tap position from those already on the system.

The settings that were designed using the real-time model of the REG-D were then implemented in the actual REG-D relays and the response of the hardware relays was compared to that of the simulation models of the REG-D relay on the same study system. The actual REG-D relays responded in the same manner to the simulation models of the REG-D relay when transformer T2 was reconnected to the network.

It can be concluded that the simulation model of the REG-D relay developed in Chapter Three can be used to determine settings for a relay that would be used in an actual distribution network. It should be noted that in this chapter the distribution network under study was considered at a fixed operating point. Under practical conditions, the network operating point is not constant over a twenty four hour period. Chapter Five will examine how the change of the network operating point over a twenty four hour period affects the performance of the REG-D relay when the $\Delta\cos\varphi$ algorithm is enabled.

CHAPTER SIX

Testing the Performance of the Δcosφ Algorithm Under Realistic Network Conditions

6.1 Introduction

Thus far the REG-D relays have been shown to be able to regulate the secondary voltages of distribution transformers as well as the circulating currents that may flow between parallel transformers. In Chapter Five it was shown how to best design the settings for the REG-D relay when the relay is operated in a meshed distribution network. The network used to test the ability of the REG-D relay to control circulating currents was considered at a constant operating point in Chapter Five. The power factor angles measured by the relays at the terminals of the transformers were therefore constant during the tests considered in Chapter Five.

Distribution networks supply different types of loads, from residential loads to industrial loads. These types of loads often vary over a period of time. The genuine variation of the loads would result in the variation of the power factor measured by the REG-D relays at each transformer's secondary terminals. In such cases, where the power factor varies, the Δcosφ algorithms of the REG-D relays may misinterpret the genuine changes in power factor as being due to the presence of circulating currents and thus respond to them incorrectly.

Chapter Six examines the impact of changes in the measured power factor on the performance of the REG-D relays under realistic network conditions. Actual load profiles for the upper south coast distribution system were obtained from Eskom and these load profiles showed how the network loads vary over a 24 hour period. In Chapter Six the real-time model of the system is extended so as to represent the true time-varying nature of the active and reactive components of each of the loads in the distribution system under study. In order to study the interaction between the REG-D relays, customized models and techniques were developed for the Real Time Digital Simulator and these techniques will also be discussed.

6.2 The Challenge of Time Varying Network Loads

Figure 31 that is shown in Chapter Five, demonstrates how real-time simulator studies are able to predict the impact of the REG-Ds' control action following significant network topology changes. It was reasonable to assume, for the studies conducted in Chapter Five, that the network loads in the distribution network were of fixed magnitude and power factor, since the time frame of those studies was in the order of several minutes. Those studies showed that when the network power factor is constant, the REG-D relays are able to correctly interpret the change in the power factor at each of their transformer's secondary terminals as being due to the presence of circulating current.

However, as it was mentioned in the above section, the network power factor often varies during a daily load cycle. This change in the network power factor is due to the variations in the network loads. The variations of network loads could lead to the relays misinterpreting genuine changes of the power factor as being due to the presence of circulating currents. When the REG-D relays misinterpret the changes of the network power factor they could operate incorrectly.

In order to study the performance of the REG-D's $\Delta\cos\varphi$ algorithm under more realistic network conditions, where the network loads vary, an extensive load data gathering exercise was undertaken. Actual load data for the loads shown in Figure 27 were obtained from Eskom Distribution in the Eastern Region. Figure 33 shows the active and reactive power variations of two particular loads, L_1 and L_2, from the system shown in Figure 27 during winter over a 24-hour period. Similar measured load data was also gathered for loads L_3 to L_5 for the same winter 24-hour period.

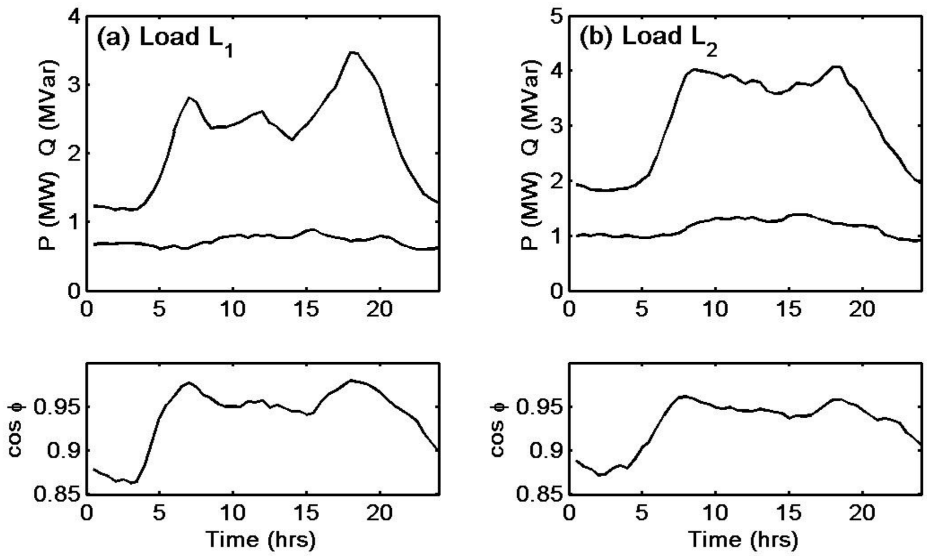

Figure 33: The measured time varying loads: (a) at L_1; (b) at L_2. (data courtesy of Eskom Distribution)

In Figure 33 it can be seen that during a typical 24-hour load cycle the active component, of load L_1 and load L_2, varies considerably in size whilst there is much less variation in the size of the reactive component of both loads. Also, it can be seen from the above figure that the power factors of the two loads vary between 0.87 and 0.98 during the daily load cycle. The other loads (loads L_3 to L_5) in the network showed similar trends over a 24-hour load cycle.

In order to test the behaviour of the REG-D's $\Delta\cos\varphi$ algorithm under conditions where the load profile varies over a 24-hour cycle, it was necessary to modify the real-time model of the system so that the loads represent the true time-varying nature of the reactive and active components of the actual loads over a 24-hour cycle. Also, in order to study the interactions between the REG-D relays during a 24-hour load cycle it was necessary to allow the simulations to run over a 24-hour period. These requirements presented challenges that needed customized models and techniques to be developed for the Real Time Digital Simulator in order to perform the studies.

In the RTDS environment user-defined functions were developed to replicate the time varying behaviour of both the active and reactive components of power at each of the five load points. For cases where the RTDS library of pre-developed power system models are not adequate for the needs of a particular study, the RTDS environment provides the user with tools for developing custom real-time models. These tools allow the user to develop the user-defined real-time models using a subset of the C programming language.

Using these tools, a customized real-time simulation model that outputs a piecewise linear approximation to any desired curves of active and reactive power versus time was developed. This model was developed such that the user enters the coordinates of 10 or more points along the desired curves of active power and reactive power versus time. These points would be from a set of actual load measurements such as those shown in Figure 33. The user can also, if desired, enter an accelerating factor that would allow the full 24-hour load cycle to be reproduced over any required time period. A piecewise linear approximation of load L_1 that was reproduced by the custom real-time model is shown in Figure 34(b).

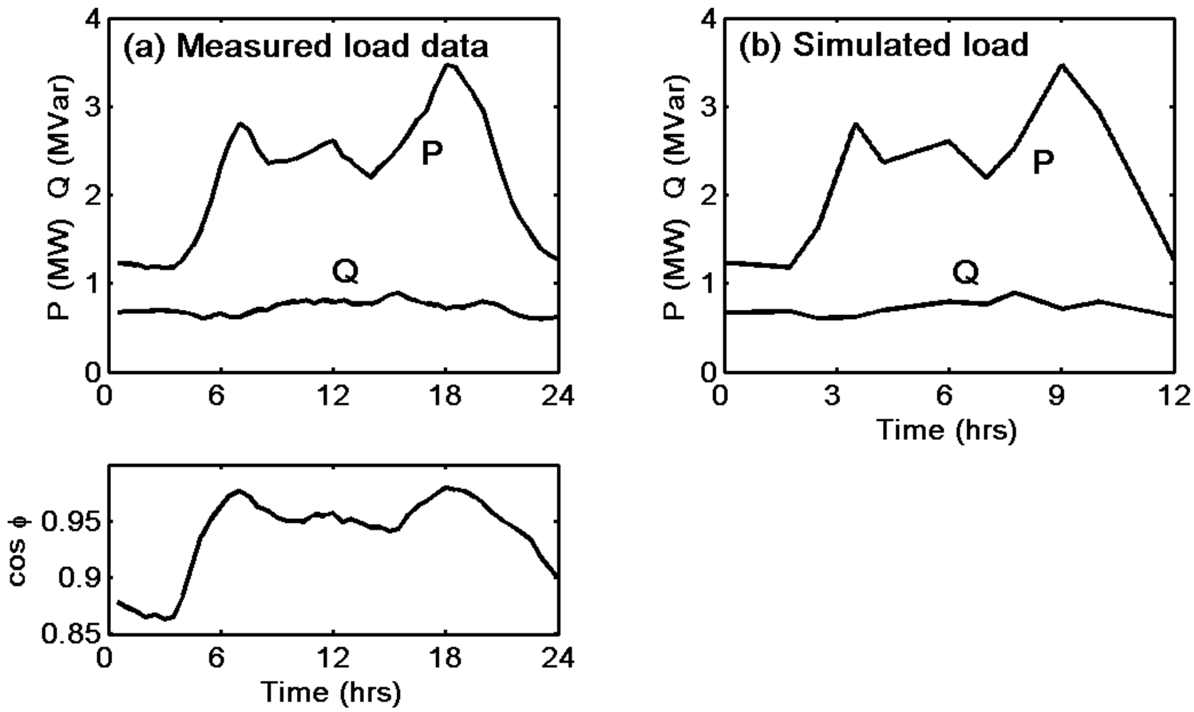

Figure 34: (a) Actual time varying load at L_1 obtained from Eskom data; (b) a piecewise linear approximation of the time-varying load at L_1 using the custom real-time model and an acceleration factor of 2.

In order to study the performance of the REG-D relays in a network where the network loads are time varying it is important to carry out the studies for a full 24-hour period. The Real Time Digital Simulator carries out the solution of power system models at time steps of 50 to 100 μs, as is typical of electromagnetic transient studies. In the RTDS environment the user can observe the behaviour of the variables of interest using a software interfacing program (Run Time) on the host PC.

The user can observe these variables in two modes: slow-changing variables can be displayed on software meters which are updated automatically by the real time simulator at a rate of about one data point per second; the user can select variables that will be gathered over a specified time period, with the data gathering commencing at any desired point during the simulation, and the variables would be displayed on x-y plots on the host PC as soon as the data gathering from the simulation is complete.

The results shown in Figure 31 in Chapter Five, for example, were obtained using the latter method. The challenge with collecting data in this mode is that there are restrictions on the amount of data that can be transferred between the RTDS rack and the host PC. The restrictions are there so that the data gathering does not interfere with the real-time execution of the simulation algorithms running on the RTDS rack. To limit the amount of data transferred the user is able to select a downsampling interval, for data gathering, of up to 128 real-time simulation time steps. However, at the time this work was carried out, the maximum downsampling interval available in the RTDS Run Time program was 128 steps.

For the study shown in Figure 31 the real-time simulator was solving the system model every 100 μs and the data shown was sampled once every 128 simulation time steps. This meant that the data shown in Figure 31 was sampled every 12.8 ms. Thus, for the time period of 300 seconds considered in the study of Figure 31 each variable shown in the results comprises a vector of approximately 23 000 data points, and these data points were transferred in one batch from the RTDS rack to the host PC. It then becomes evident that downsampling data from a real-time study that is conducted over a 24-hour load cycle would generate unmanageable data records if the downsampling interval used is once every 128 real-time simulator time steps.

However, the RTDS environment also provides C-like scripting language tools that can be used to automate common tasks conducted from the user interface program on the host PC. In order to suit the demands of long-term simulation studies these scripting tools were used to write a script file that would alter the manner in which the data is gathered from the RTDS rack and saved on the host PC.

The custom script file was used to reconfigure the simulator to: (i) save data associated with a single point in time during the real-time simulation instead of saving a vector containing the behaviour of the variable over a time period; (ii) save these single-time step (scalar) data values automatically at any desired downsampling interval relative to the real-time simulation's time step. This approach of saving data from the RTDS racks for long-term real-time simulation studies is illustrated in Figure 35.

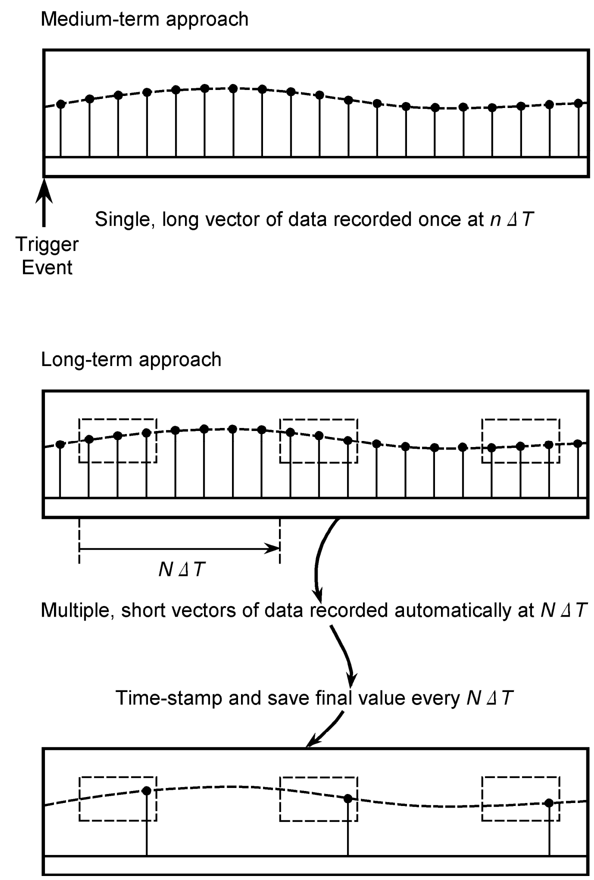

Figure 35: Default approach to saving data on the RTDS versus customized downsampling approach developed for long term simulation studies [22].

Figure 35 illustrates the difference in the approach of downsampling and saving data obtained from long-term and medium-term real-time simulator studies. In medium-term studies the data of a particular variable is downsampled following some pre-set trigger every n simulation time steps, where $n \leq 128$. The simulator then records the data that was sampled into a long vector. After the data has been recorded into a vector, the user can manually save the data to disk.

In long-term studies the simulator is prompted by the script file that was developed to record a much shorter vector every N time steps. This vector contains a shorter time record of the variable's behaviour. The script file would then automatically time stamp and save the last element from the recorded vector. It should be noted that the data that is recorded by the script file is shorter than that would be recorded by the simulator. Also the script file only saves the last element of the vector. Using this technique it is possible to gather data from the real-time simulation at much longer sampling intervals $N\Delta T$ and record several hours' worth of system behaviour.

6.3 The Response Of the REG-D to Time Varying Loads

6.3.1 Fixed Network Power Factor Settings

In order to assess the performance of the REG-D relays under long-term (24-hour) varying load conditions, the customised techniques described in the previous section were used. A model of the distribution system shown in Figure 27 was used to test the performance of the REG-D relays under the said network conditions. The custom-written load models were used at each load point to reproduce the known variations in these loads in an actual 24-hour load cycle. From Figure 34 it can be seen that the rate at which the loads in the network vary versus time over a 24-hour period is somewhat slower than the response time of the REG-D relays. Thus, an accelerating factor of 3 was used when testing the performance of the REG-D relays to varying network load conditions. An accelerating factor of 3 implies that the actual 24-hour load cycle was reproduced in the real-time simulation over 8 hours.

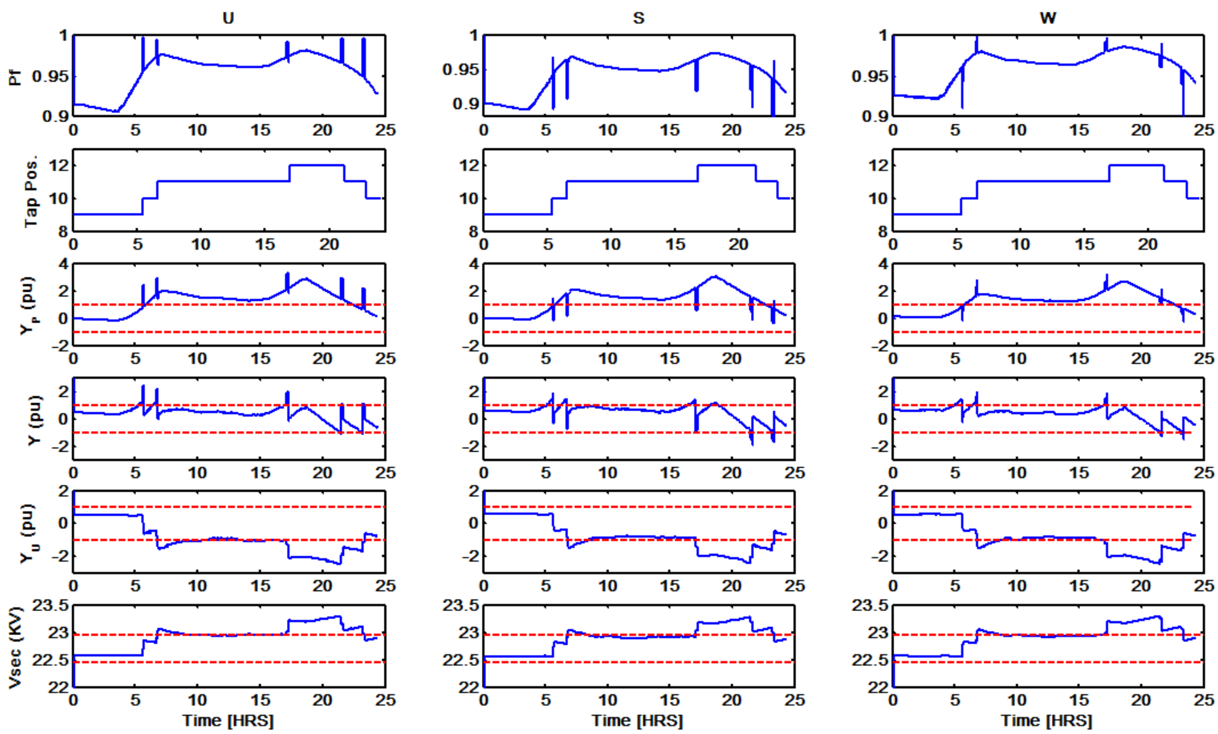

Figure 36: Real-time simulator study to investigate the response of REG-Ds to the actual 24-hour load cycle in the distribution system; $\cos\varphi_{set}$ values are set to conditions at t = 0 hours.

It is important to note that in tests such as that shown in Figure 36, there was no network disruption considered, and neither were there any actual circulating currents between the transfomers; the tap changes that occurred were in response to the load variations in the network over the 24-hour load cycle. Figure 36 shows the response of the REG-D relays to variations in the network loads over a 24-hour load cycle. The set point power factor of the REG-D relays was set to the point of the lowest load level (at t = 0 hours). The error signal Y_p

from the $\Delta\cos\varphi$ algorithm is therefore very close to zero between 0 to 3.5 hours. This implies that the relays do not detect any circulating current, which is correct as the transformers are at the same tap positions and their secondary voltages are within the permissible deviation, which is shown by the dotted lines.

The network loads increase between time t = 4 – 7 hours, and (as discussed in Section 6.2) during this pickup in network load, the power factors of the loads themselves actually change. As the power factor changes the REG-D relays misinterpret the change in power factor as being caused by the presence of circulating current. At 5.5 hours the secondary voltages of all three transformers are within the permissible deviation but the transformers are tapped up incorrectly. This is due to the fact that the $\Delta\cos\varphi$ algorithm misinterprets the change in the network power factor as being caused by circulating current, thus resulting in an incorrect error signal Y when Y_P is added to Y_U.

As the load continues to increase the voltage is still within permissible deviation but the transformers continue to tap up. The secondary voltages of the transformers are slightly out of the permissible deviation between 7 and 9 hours. The load continues to increase between 15 to 20 hours and even though the transformers should not tap up as far as they do during this period, as their secondary voltages are close to the permissible deviation, the REG-D relays continue to tap the transformers up resulting in their secondary voltages exceeding the legal limits.

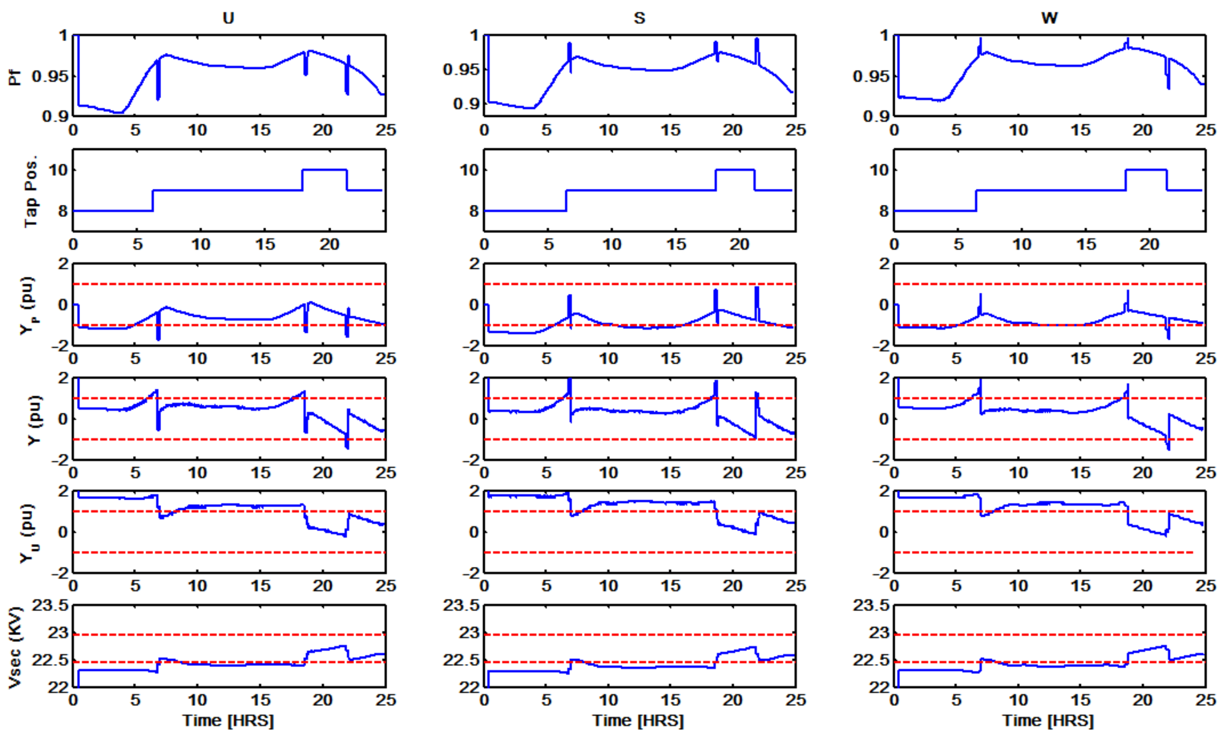

Figure 37: Real-time simulator study to investigate the response of REG-Ds to the actual 24-hour load cycle in the distribution system; $\cos\varphi_{set}$ values are set to conditions at t = 20 hours.

Figure 37 shows a similar study to that shown by Figure 36, but with the $\cos\varphi_{set}$ values used in the REG-Ds in the study of Figure 37 set to match the load conditions that occur in the network at t = 20 hours. With this change in $\cos\varphi_{set}$ values, during low load conditions at t = 0 hours the REG-D relays now misinterpret the measured power factor as being caused by circulating current, and they do not allow the transformer to tap up so that the voltage can be returned to within the permissible deviation. The secondary voltage levels of the transformers are still within the legal limits even though they are out of the permissible deviation set within the relays during this period of the day. When the load increases between 6.8 to 18.5 hours the REG-Ds correctly tap the transformers up and the transformers' secondary voltages are close to being within the permissible deviation. The network loads increase from 18 hours and the REG-Ds tap the transformers up resulting in the secondary voltages of the transformers being within the permissible deviation.

The two studies that have been discussed above show that if there is a significant difference between the $\cos\varphi_{set}$ value specified in the REG-Ds and the network power factor measured by the REG-D relays, this difference could cause the REG-Ds to operate incorrectly. A final study was carried out to investigate whether the challenges encountered in Figures 36 and 37 could be mitigated by using fixed network power factor settings for the REG-Ds that correspond to some intermediate load condition during the day. The fixed $\cos\varphi_{set}$ settings for this third study were chosen to correspond to load conditions at t = 10 hours. The results of this study are shown in Figure 38.

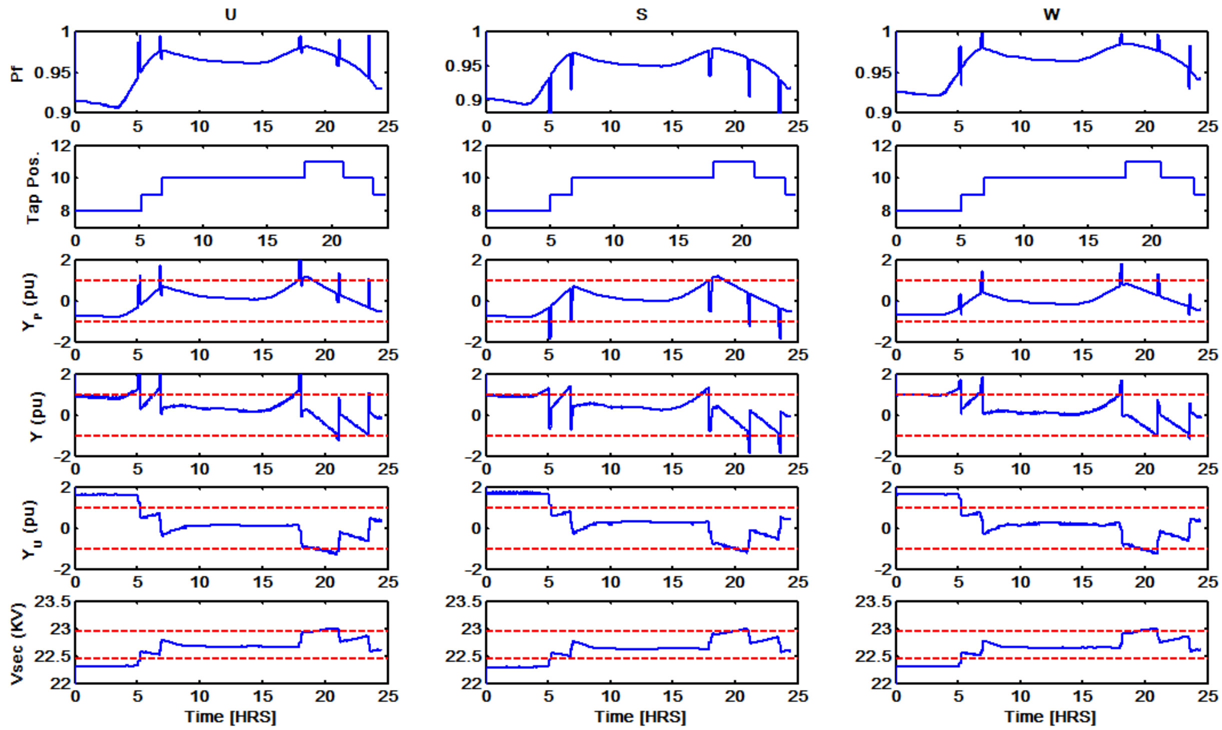

Figure 38: Real-time simulator study to investigate the response of REG-Ds to the actual 24-hour load cycle in the distribution system; $\cos\varphi_{set}$ values are set to conditions at time = 10 hours.

Figure 38 shows the results of the test where the $\cos\varphi_{set}$ values were set to correspond to conditions at t = 10 hours. This point in time was chosen as being representative of the load power factors through much of the daily load cycle. When the results shown in Figure 38 are compared to those shown in Figures 36 and 37, it can be seen that the voltage regulation of all three transformers has improved when the $\cos\varphi_{set}$ values are chosen to correspond to a point in time that is more representative of the load power factors throughout a daily load cycle. It can be seen in Figure 38 that when this approach of choosing the $\cos\varphi_{set}$ values is used, the secondary voltages of the transformers stay for the least amount of time out of the permissible deviation. Nevertheless, although Figure 38 has demonstrated how best to choose a fixed value of $\cos\varphi_{set}$ to minimise the voltage regulation errors caused by changing network power factors, the results show that there are still voltage regulation problems as a result of the fixed $\cos\varphi_{set}$ settings being too far from the actual network load conditions during periods of the daily load cycle.

The REG-D relays do offer a facility for tracking slow changes in the network power factor in order to alleviate the problems shown in Figures 36 and 37 (and to a lesser extent in Figure 38). This facility will be investigated in the following sub section.

6.3.2 Slow Tracking of Network Power Factor

As it was mentioned above the REG-D relays do offer a facility for tracking slow changes in the network power factor. This feature is provided to improve the operation of the relays during a 24 hour load cycle. At the time of this work, there was no technical information available on how the feature tracks the changing network power factor and dynamic tests needed to be carried out in order to understand how the slow tracking feature operates.

The slow tracking facility to be discussed in this subsection is a proprietary algorithm within the REG-D relay whose details the author was not privy to. Dynamic tests were performed by the author on the REG-D relay with this algorithm enabled primarily in order to get a feel for what the algorithm does and what its limits are, and not to attempt to characterise the algorithm in detail. As a result of these tests, and during subsequent correspondence with the manufacturer of the REG-D regarding the slow tracking facility, it was discovered that the range of values over which the settings parameter $\cos\varphi_{set}$ is allowed to vary has been deliberately restricted by the manufacturer to ensure stability of the regulation algorithms.

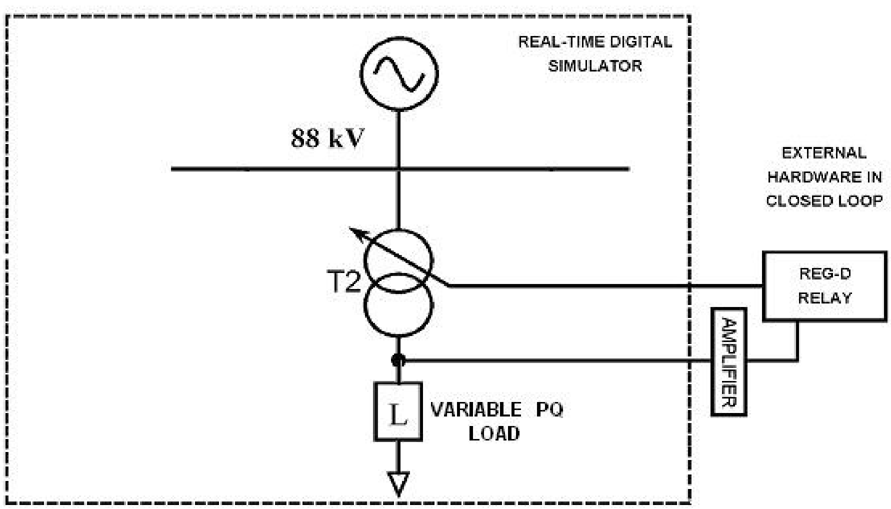

Figure 39: The approach used to test the power factor tracking feature.

Figure 39 shows the simplified test system that was configured on the real-time simulator to test the dynamic performance of the REG-D's power factor tracking algorithm. This test system comprises a single tap-changing transformer connected in closed-loop with a single hardware REG-D relay. The transformer is feeding a variable PQ load. The variable PQ load was used to vary the power factor measured by the transformer.

In order to measure the dynamic performance of the REG-D's power factor tracking algorithm several tests were carried out. In the first study the $\cos\varphi_{set}$ value of the relay was set to match, as closely as possible, the starting value of the load power factor. The load power factor was then subjected to a step change and the size of the step change in the load power factor was chosen to correspond to the range of network power factor changes encountered in the distribution network under study. The REG-D relays were allowed to adjust their $\cos\varphi_{set}$ values via their power factor tracking algorithm and the step-up and step-down responses were measured.

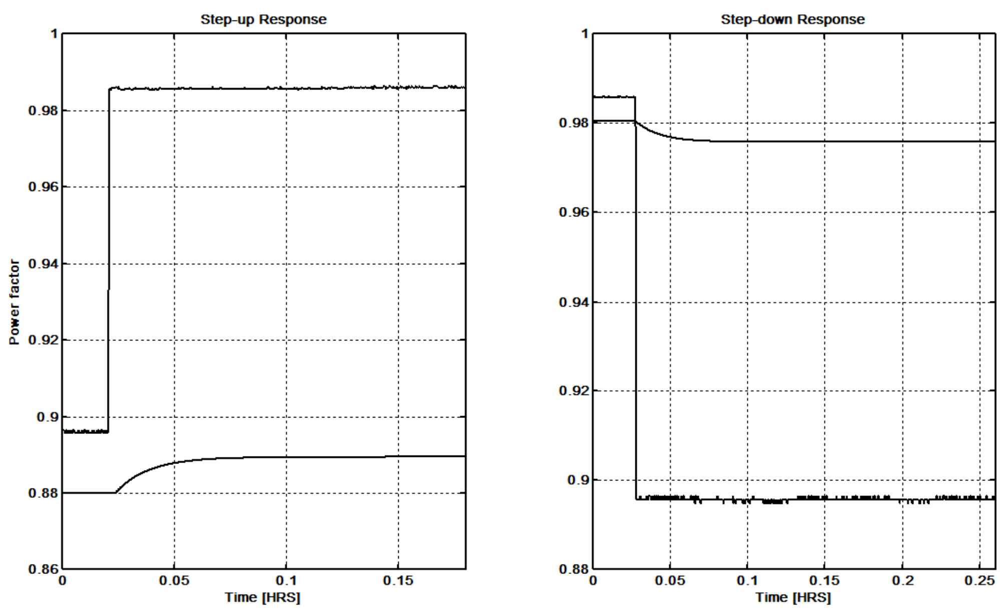

Figure 40: The measured step response of the power factor tracking algorithm of the REG-D.

Figure 40 shows the step-up and step-down responses of the power factor tracking algorithm of the REG-D relay. From the figure it can be clearly seen that the tracking algorithm is limited in the range of values over which it can track the actual changes in load power factor, for both the step-up and step-down tests. In the second study the relay was again started from a $\cos\varphi_{set}$ value that corresponds to the initial condition in the load. The power factor was then subjected to a linear ramp change. The rate of change of the power factor with time as well as the range of values over which the power factor varies during this ramp test were chosen to be similar to that of the actual behaviour of the network power factors in the distribution system under study during the fastest changing period of the 24-hour load cycle.

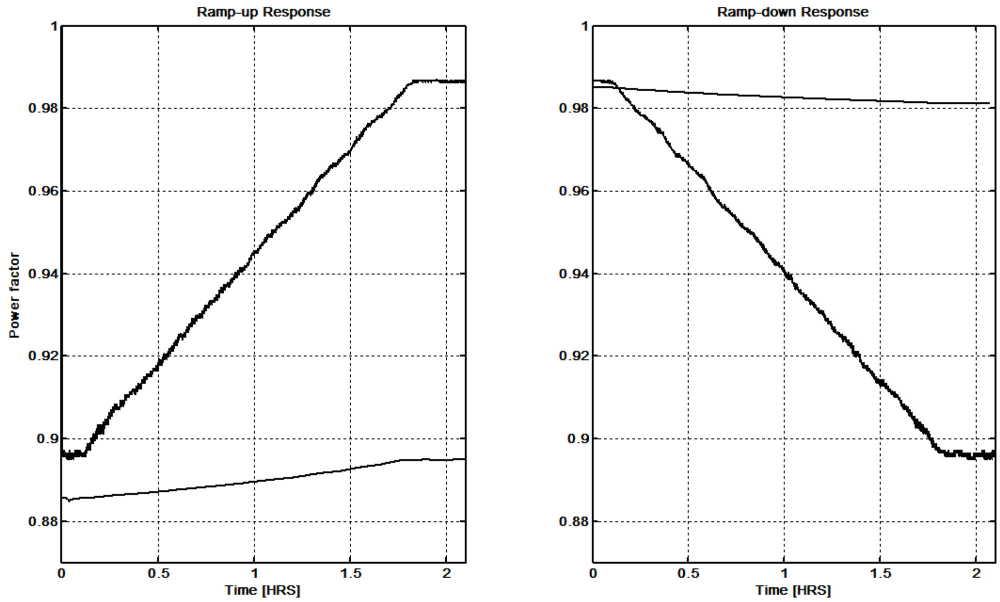

Figure 41: The measured ramp response of the power factor tracking algorithm of the REG-D relay.

In Figure 41 it can be seen that power factor tracking algorithm can be set by the user to respond sufficiently rapidly in tracking the expected rate of change in network power factor but once again, the amplitude range over which the setting is allowed to change is restricted. In Figures 40 and 41 it can be seen that the range over which the $\cos\varphi_{set}$ is allowed to change is significantly smaller than the actual range of the variations in network power factor in the study system. The next section will study the performance of the REG-D relay in an actual distribution network when its power factor tracking algorithm is enabled.

6.3.3 Testing the REG-D's Power Factor Tracking Algorithm

The tests that were carried out with the REG-Ds having fixed power factor settings ($\cos\varphi_{set}$) while the network loads vary over a 24 hour load cycle revealed that the REG-Ds misinterpret the genuine changes in the network power factor as being caused by circulating current, and this results in the REG-Ds responding incorrectly to these changes in the network power factor. It was seen that this incorrect operation of the REG-Ds can be mitigated, to a certain extent, by choosing a network power factor setting that is more representative of the load power factors throughout a daily load cycle.

Two tests were carried out to assess the performance of the REG-Ds when the power factor tracking algorithm is enabled during a daily load cycle. In the first study the network power factor settings ($\cos\varphi_{set}$) in each REG-D were set to match the point of the lowest load level (at t = 0) hours and the power factor tracking algorithm was enabled. The simulation was then allowed to run for 24 hours in order to complete the daily load cycle. Figure 42 shows the performance of the REG-Ds during a daily load cycle when the power factor tracking algorithm is enabled. The measured power factors (Pf) at each transformer's secondary terminals are indicated by the blue curves, while the power factor settings of each transformer, as they are adapted over time within the REG-Ds, are indicated by the green curves. Again it should be noted that in the following tests there was no network disruption and nor were there any actual circulating currents that flowed between the transformers; the tap changes that occurred on each transformer were in response to the load variations during the 24-hour load cycle.

When Figure 42 is compared to Figure 36 it becomes apparent that there is an improvement in voltage regulation at each transformer's secondary terminal. The secondary voltages of the transformers are within, or close to being within, the set permissible levels for most of the daily load cycle in Figure 42. In Figure 36 the secondary voltages of the transformers exceed the legal limits at 20 hours but it can be seen in Figure 42 that the transformer secondary voltages are now much closer to the desired limits even at 20 hours.

These results show that the power factor tracking feature of the REG-D relay does improve the performance of the relay in a distribution network where the network load varies over a 24 hour period. In the second study the setpoint network power factor settings were chosen to correspond to conditions at t = 10 hours and Figure 43 shows the behaviour of the relays when the power factor tracking feature has been activated. Figure 43 shows that the performance of the REG-D relays is now greatly improved when the setpoint $\cos\varphi_{set}$ values are chosen to correspond to a point in time that is more representative of the load power factors throughout a daily load cycle *and* with the power factor tracking feature also enabled.

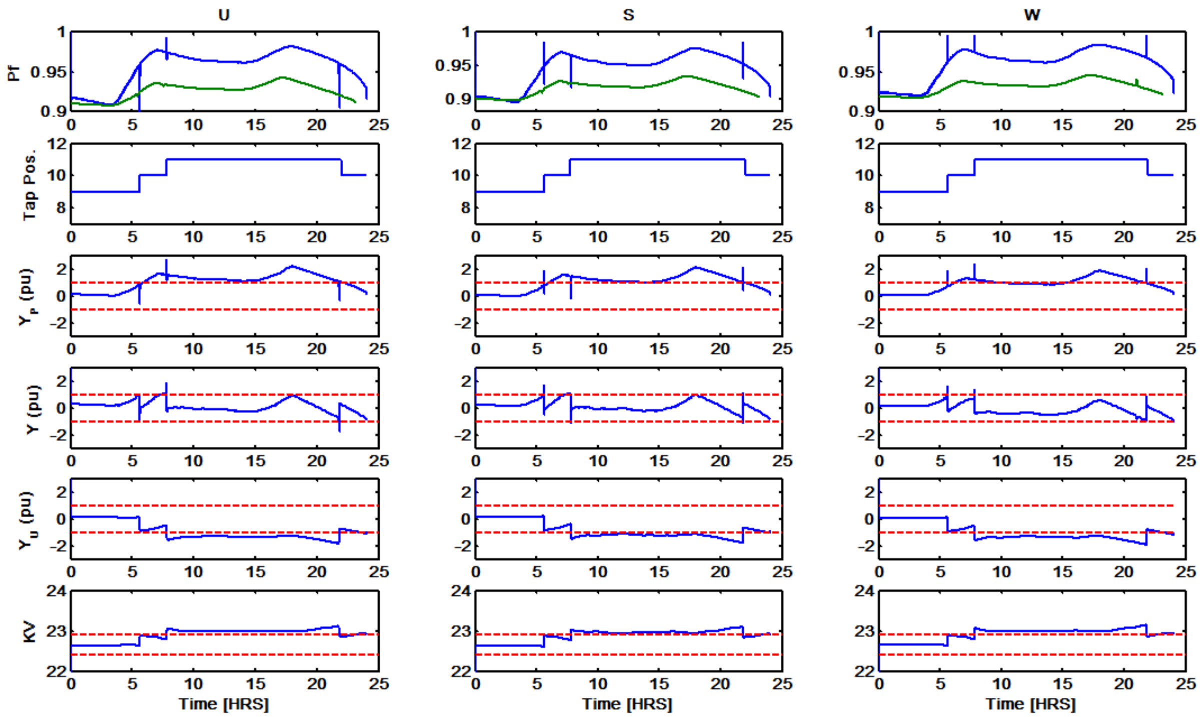

Figure 42: Real-time simulator study to investigate the response of REG-Ds to the actual 24-hour load cycle in the distribution system; $\cos\varphi_{set}$ values are set to conditions at time = 0 hours and the power factor tracking feature is enabled.

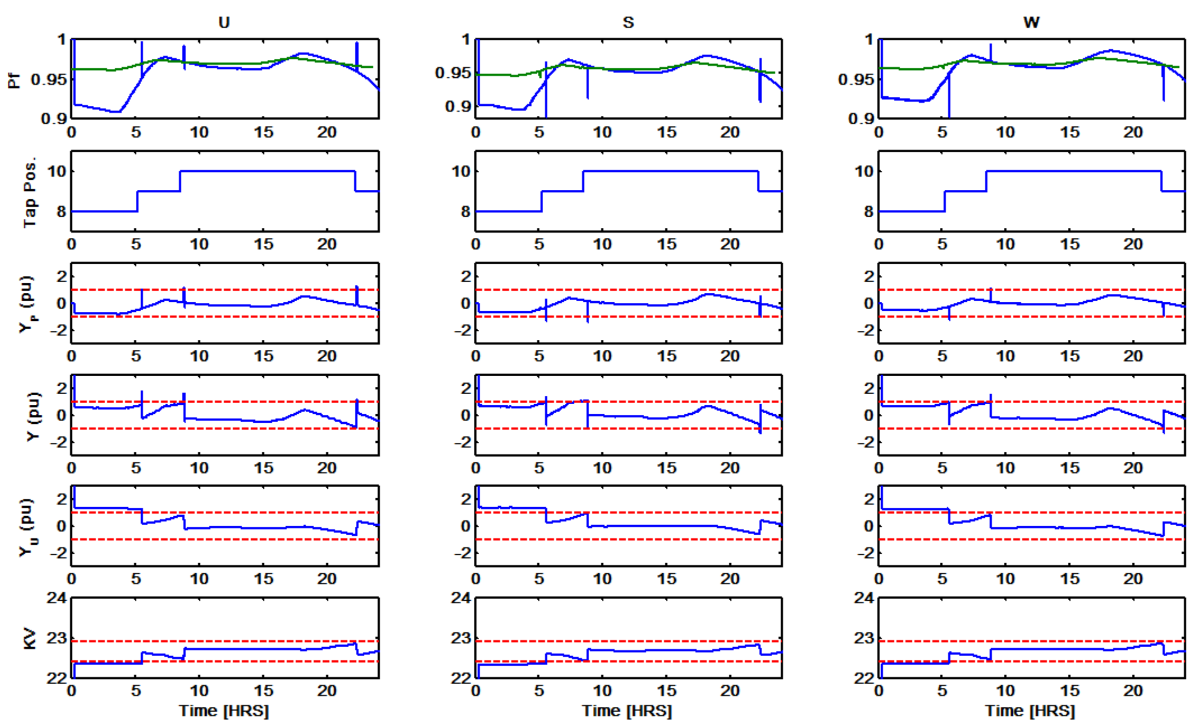

Figure 43: Real-time simulator study to investigate the response of REG-Ds to the actual 24-hour load cycle in the distribution system; $\cos\varphi_{set}$ values are set to conditions at time = 10 hours and the power factor tracking feature is enabled.

6.4 Conclusion

The RTDS library does provide pre-developed power system models that can be used as tools for carrying out power system studies. Occasionally these pre-developed power system models become inadequate for the needs of some power system studies. In such cases the RTDS environment does provide the user with tools for developing customized real-time simulation models that would meet the needs of that particular study.

These tools were used to develop load models that reproduce known 24-hour load profiles over any desired period. Also scripting tools that are provided in the RTDS environment were used to develop script files that would prompt the real-time simulator to save data associated with a single point in time during the real-time simulation and to save these single-time step data values automatically at any desired downsampling interval relative to the real-time simulation's time step.

These tools were used to study the performance of the REG-Ds when operated in a distribution network under the realistic (measured) load conditions experienced in practice in this chosen study system. The results obtained from the studies that were carried out indicate that regulators equipped with $\Delta\cos\varphi$ control require careful settings design. Also the results indicate that the performance of the relays with $\Delta\cos\varphi$ control is improved when the power factor tracking is enabled, although the tracking algorithm does not track the full range of network power factor changes.

CHAPTER SEVEN

Conclusion

7.1 Introduction

One of the key objectives of a distribution network is to provide power to customers at voltage levels for which their appliances and equipment will operate with acceptable levels of performance and efficiency. Poor performance and low efficiencies of customer equipment and network plant can result in loss of revenue. The dynamics of an electric power system are slow when it is operating under quasi steady state conditions, hence, significant changes in the system voltage level may occur over long periods before it is necessary to correct the voltage levels.

There are various methods that were mentioned earlier in this thesis that are used in industry in order to correct these voltage variations but this thesis has concentrated specifically on voltage regulation at the bus of an interconnected network using on-load tap changing transformers. When transformers are operated in parallel or in a meshed network topology they allow operational flexibility as well as provide security of supply. Even with these added operational benefits it is essential that the transformers continue to serve their basic function of controlling the load bus voltages. Also, parallel-connected transformers must act so as to minimize the circulating reactive current between them. The above mentioned actions must operate correctly in a multiple transformer application regardless of the system configuration changes.

In industry, various control schemes are implemented via commercially-available relays in order to control tapping up or down of a transformer tap changer. The task of making use of such relays to automate the on-load tap changers on distribution transformers so as to regulate voltages to meet the demands of the utility practice, as well as the legal requirements described above, is well understood but the issue becomes more challenging and less well-understood when multiple such transformers are connected in parallel and these transformers are tens of kilometres apart. This thesis has focussed on this technical challenge, and in particular its solution using a relay in common use by South African electric utilities, the REG-D relay.

Before the work in this thesis was conducted there was little or no industry experience of how to determine the settings for such relays and of how these relays will perform under realistic network conditions. This lack of experience was as a result of the absence of suitable tools with which to test the performance of these relays under representative conditions once their settings have been designed, prior to commissioning them in the field, in addition it was contributed to by a lack of deep knowledge regarding the theory of operation of the circulating current control algorithms on these relays. In order to address these specific shortcomings, this thesis has made use of real-time digital simulator hardware and software to allow closed-loop testing and performance evaluation of multiple voltage regulating relays on parallel-connected transformers in meshed topology distribution systems, as well as determining how to go about designing settings for such relays.

In addition, the thesis has developed a detailed dynamic simulation model of the REG-D relay that has allowed its control algorithms to be better understood by settings engineers in future, both when conducting real-time simulator tests and allowing the ability to simulate the closed-loop performance of the REG-D relay using other non-real time simulation packages more widely available in industry.

7.2 The REG-D approach to circulating current control

This thesis briefly described the different technologies that are available for controlling circulating reactive currents between parallel transformers. It was seen that the majority of these algorithms were designed to regulate voltages and circulating currents between transformers that are in the same substation. As it has been mentioned in the thesis, it becomes a challenge to regulate the secondary voltages of transformers that are kilometres apart, as well as to limit circulating reactive currents that may flow between them.

Eskom is currently using the REG-D relay for regulation of transformer secondary voltages. The REG-D relay is also currently used both to control circulating current and to regulate voltages using the Δcosφ algorithm, but this algorithm has the advantage that it does not require any communication links between the relays in the network. This feature of the REG-D relays would allow for cost-effective regulation of network voltages and control of circulating currents in a meshed network topology where the transformers would be tens of kilometres apart. It is for these reasons that this particular relay has been chosen for a detailed study in this thesis.

The origin of the circulating current problem was introduced by means of the simple case of two similar transformers connected in parallel as presented in Chapter Two. When two such transformers with equal impedances are at different tap positions, such that their turns ratios are different, circulating current will flow between the two transformers. It was discussed that circulating reactive currents will flow between transformers in a distribution network when the transformers are at different tap positions and that these circulating currents are limited by the impedances between the transformers. When the circulating currents that flow between parallel transformers at different tap positions are not controlled adequately, these circulating currents could result in one of the transformers being overloaded and thus tripping out on overload or oil-temperature protection. Circulating reactive currents also cause a loss in sensitivity of the transformer's secondary voltage to tap changes at the affected transformers under conditions of light loading.

In Chapter Four the REG-D voltage regulating algorithm, circulating current algorithm and the time programs were modelled in detail using a real-time simulator. The performance of the simulation model of the REG-D's voltage regulation and circulating current control algorithms developed in the thesis was then compared to that of the actual REG-D relay and it was found that the simulation model of the REG-D was able to regulate both voltage and circulating current.

In Chapter Four the performance of the voltage regulation and circulating current control algorithms of the REG-D was initially tested in the simplest possible network that comprised two transformers connected to the same bus supplying a constant PQ load, since the focus in these early studies was on developing a model of the REG-D relay and on understanding the relay itself. In Chapter Four and Five it was then investigated how the practical REG-D relay and its simulation model would perform in a realistic distribution network. The performance of the simulation model of the REG-D relay was compared to that of the actual hardware relay in both chapters. The simulation model that was developed in this thesis for the real-time simulator could be ported to other simulation packages to test the performance of the relay under realistic distribution network conditions.

As a result of the work presented in Chapter Four of this thesis, it can now be concluded that a sound understanding exists of how the internal algorithms of the REG-D relay operate, and in particular how the settings chosen by user, and the dynamic limitations within the relay algorithm, affect the performance of the relay under closed loop conditions, and under practical load varying conditions experienced in the field. In other words, with the assistance of the dynamic simulation model of the relay developed in Chapter Four of this thesis, it is now possible to better understand the reasons for the behaviour of multiple REG-D relays observed during complex real-world field test simulations such as those carried out in subsequent chapters of the thesis. This will be of similar benefit to practicing engineers in future.

In Chapter Five, the real-time model of Eskom's Upper South Coast distribution system was studied at a fixed operating point (that is, with constant network loads) and the settings of the $\Delta\cos\varphi$ algorithm were designed for that fixed operating point and tested using the real-time simulation model of the REG-D relay developed in Chapter Four. The real-time model of the REG-D was able to regulate the circulating currents that flowed between the transformers of this study system after one of the transformers of this system was reconnected to the network at a different tap position from those already on the system. The reason that a single, fixed-load operating point was considered in the studies of Chapter Five was to re-confirm the results of earlier, introductory studies by others on the same network, with the hardware REG-D relays, and with the newly-developed simulation model of these relays, before considering studies into more realistic network conditions in subsequent chapters.

The fact that earlier studies conducted by others on this distribution network could be repeated using both the hardware REG-Ds and the simulation model of the REG-Ds established the necessary confidence in both the connection and hardware-in-loop testing methods being used for the real relays, and the technical correctness of the real-time simulation models of the real-time simulation models of the relays developed in Chapter Four. It was thus concluded that the simulation model of the REG-D relay developed in Chapter Four could be used to determine settings for a relay that would be used in an actual distribution network.

Chapter Six examined the impact of changes in the measured power factor on the performance of the REG-D relays under realistic network conditions. Actual load data for the upper south coast distribution system were obtained from Eskom and used to plot load profiles which show how the network loads vary over a 24 hour period in this study system. In Chapter Six the real-time model of the system was extended so as to be able to include a representation of the true time-varying nature of the active and reactive components of each of the loads in the distribution system under study based on the data gathered from Eskom. In order to study the interaction between the REG-D relays, customised models and techniques were also developed for the Real Time Digital Simulator to allow much longer (24-hour) real time studies.

These customised models and techniques were used to study the performance of the REG-Ds when operated in a distribution network under realistic load conditions experienced in practice. The results of these studies have shown, for the first time, the effect that realistic changes in network loads, and in particular their power factors, during a normal daily cycle have on the performance of the REG-D's circulating current control algorithm. In addition, because of the development of the simulation model of the REG-D in this thesis, it was not only possible to show what impact load variations have on the performance of the REG-D's $\Delta\cos\varphi$ algorithm, but also to show why this algorithm is affected by load variations in this way, and hence to provide the insight needed to minimise the effect of load variations by means of appropriate settings.

Hence, from the results obtained from the studies that were carried out in Chapter Six it is now known that regulators equipped with $\Delta\cos\varphi$ control require careful settings design on a case-by-case basis. Also the results indicate that the performance of the relays with $\Delta\cos\varphi$ control is improved when the power factor tracking is enabled, although the tracking algorithm is deliberately restricted by the manufacturer so as to prevent it from tracking the full range of network power factor changes.

Not only have the studies presented in this thesis highlighted the need for careful settings design of the $\Delta\cos\varphi$ algorithm on a case-by-case basis, but they have provided the necessary insight as to how to go about doing such settings. In particular, it has been shown that in order to cater for varying power factor loads the $\Delta\cos\varphi_{set}$ setting in the $\Delta\cos\varphi$ algorithm should be chosen to correspond to a value of power factor that corresponds to the network loads' behaviour during the middle of the daily load cycle, rather than that during very low load or very high load periods. This settings approach in conjunction with the use of the limited-range $\cos\varphi_{set}$ tracking feature on the REG-Ds, allows the adverse effect of daily variations in network power factor on the voltage regulation function of the REG-Ds to be minimised to within acceptable legal limits.

7.3 Conclusion

In the thesis a detailed model of the REG-D's $\Delta\cos\varphi$ and voltage regulating algorithms was developed successfully using the RTDS. The performance of the model was tested in a simple distribution network and it was found to be within acceptable tolerances when compared against practical relays with the same settings. Furthermore, the simulation model was used to design settings for the actual relays. These settings were applied to actual relays and the performance of the REG-D relays was tested under realistic network conditions. Under realistic network conditions the REG-D relay was found to misinterpret genuine changes in the network power factor as being caused by circulating current. The relay thus operated in an undesired manner by changing tap positions when it should not have.

The REG-D relay provides a feature that allows the relay power factor setting to track the changes in the network power factor. This feature was subjected to dynamic response tests and the tests revealed that the feature is deliberately restricted by the manufacturer from fully tracking the actual changes in the network power factor. From correspondence with the manufacturer it was established that this restriction was set intentionally for stability reasons. This restriction meant that the settings for the $\Delta\cos\varphi$ algorithm had to be chosen carefully. Upon further testing of the response of the REG-D relay to realistic network conditions, with the power factor tracking feature enabled, it was established that it is best to choose a power factor setting that is the most representative value during a typical load cycle, and to allow the adaptive tracking feature to vary the set point value, to the extent allowable, around this nominal value.

The simulation model of the REG-D relay that was developed in the thesis using the RTDS may be ported to other simulation packages and can be used by practicing engineers to design settings for the relays that would be installed in an actual distribution network. The tests that were conducted in the thesis have shown that REG-D relays that have settings designed using the developed simulation model would perform to within acceptable tolerances in a distribution network.

7.4 Recommendations

A detailed simulation model of the relevant REG-D relay's algorithms was developed using the Real-Time Digital Simulator (RTDS) and this simulation model was verified in the thesis. The response of the REG-D relay to changes in the network topology was investigated as well as its response to realistic variations in network loading conditions. Techniques for studying the performance of the relays over long time periods using the RTDS were developed. The effects of different REG-D settings on the response of the relays during realistic network conditions were investigated in the thesis.

It was seen that the circulating current control algorithm is sensitive to changes in the network power factor angles. For further study it is recommended that a similar study conducted in the thesis be done in a network that has more underground cables, in order to test the performance of the relays in such networks since the capacitance of such cables could influence the network power factor variations seen by the REG-Ds.

This thesis studied the control of voltage and circulating current between transformers that are of the same MVA ratings and with equal leakage reactances. It is recommended that a study with transformers that have unequal impedances and are not similar (for example transformers with different MVA ratings and unequal number of tap positions) should be conducted to test the performance of the REG-D relay in such network topologies. Also it is recommended that the REG-D simulation model developed in this thesis be ported to other simulation packages and a similar studies to those conducted in this thesis be carried out.

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APPENDIX A: Testing the Performance of the Simulation Model of the REG-D Relay

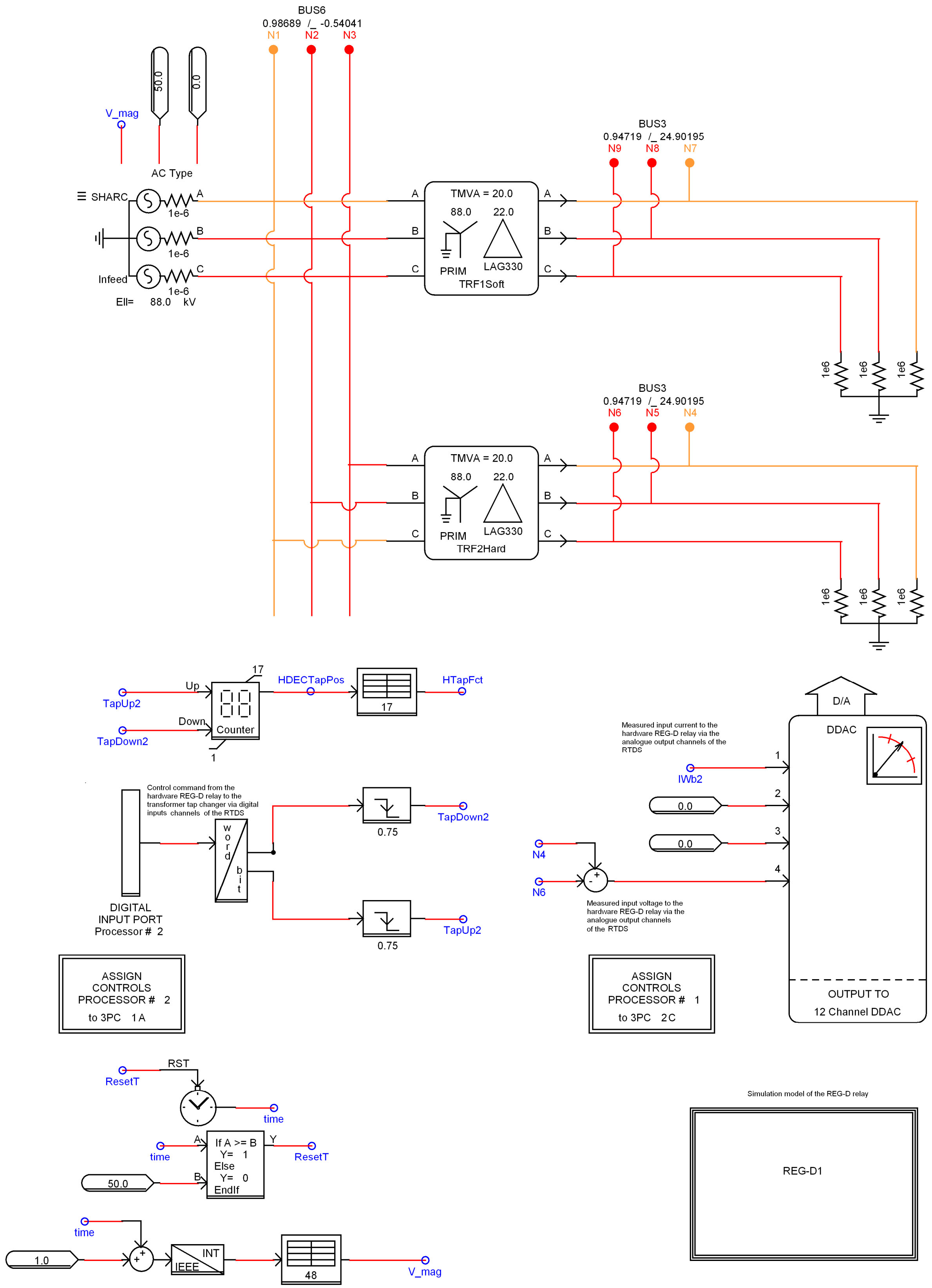

Figure A1: Real-time simulator testing of the simulation model of the REG-D algorithms.

APPENDIX B: REG-D's Δcosφ Algorithm Settings

Table B.1: Fixed network loads for design of Δcosφ algorithm in Chapter Four.

Load	Power (MW)	Power Factor
L_1	8.8	0.96
L_2	7.2	0.94
L_3	9.75	0.97
L_4	5.3	0.96
L_5	1.77	0.99

Table B.2: Measured network $\cos\varphi_{set}$ settings at W, S and U substations in Chapter Four.

Substation	W	S	U
$\cos\varphi_{set}$	0.9705	0.9584	0.9567

Table B.3: Designed I_{circ_perm} settings at W, S and U substations in Chapter Four.

Substation	W	S	U
I_{set_perm}	18 A	18 A	18 A

APPENDIX C: Calculations of the Transformer Loading

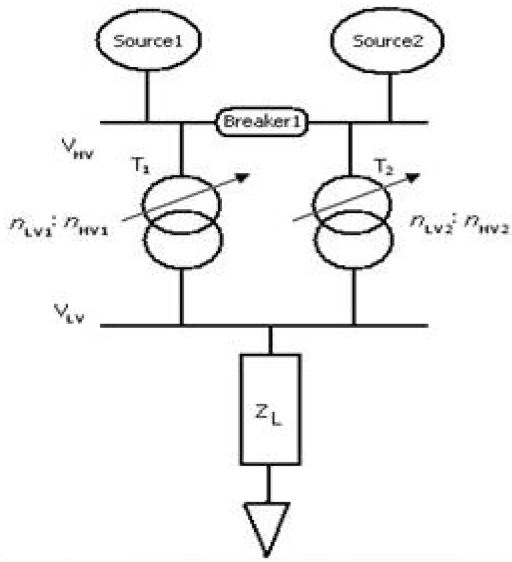

Figure C1: Two parallel transformers T1 and T2: 88/22 kV 20MVA , Z = 10%

Z_{BASE}: $\dfrac{V^2}{S} = 24.2\ \Omega$

Z_{T1} and $Z_{T2} = 2.42\ \Omega$

$V_{T1} = \dfrac{22}{\sqrt[2]{3}} \times 1.0\,\text{kV}$ and $V_{T2} = \dfrac{22}{\sqrt[2]{3}} \times 1.1\ \text{kV}$

Transformer T2 is at tap position 13 and T1 is at tap position 5

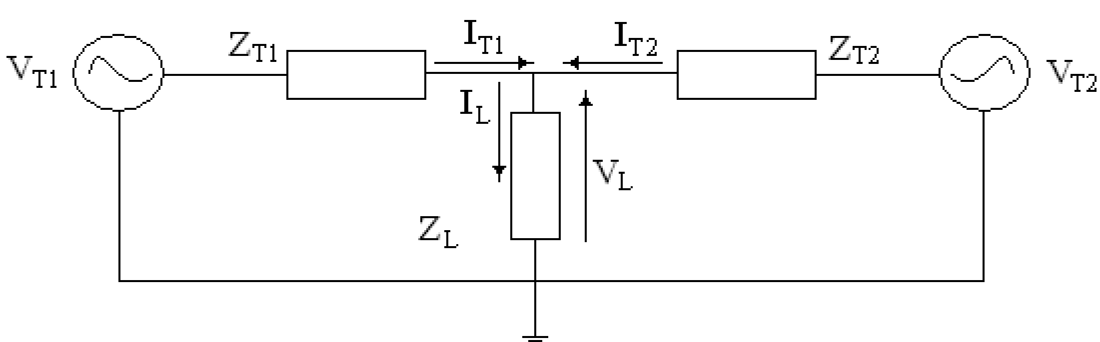

Figure C2: The equivalent circuit of the network shown in Figure C1

By performing nodal analysis the following equation is obtained:

$$\frac{\overline{V}_L - \overline{V}_{T1}}{\overline{Z}_{T1}} + \frac{\overline{V}_L}{\overline{Z}_L} + \frac{\overline{V}_L - \overline{V}_{T2}}{\overline{Z}_{T2}} = 0 \qquad \text{(C1)}$$

By manipulating Equation C1 the following equation is obtained:

$$\frac{\overline{V}_L}{\overline{Z}_{T1}} + \frac{\overline{V}_L}{\overline{Z}_L}\frac{\overline{V}_L}{\overline{Z}_{T2}} = \frac{\overline{V}_{T2}}{\overline{Z}_{T2}} + \frac{\overline{V}_{T1}}{\overline{Z}_{T1}} \tag{C2}$$

By making $\overline{V}_L$ the object of Equation C2, Equation C3 is obtained:

$$\overline{V}_L = \frac{\left(\dfrac{\overline{V}_{T2}}{\overline{Z}_{T2}} + \dfrac{\overline{V}_{T1}}{\overline{Z}_{T1}}\right)}{\left(\dfrac{1}{\overline{Z}_{T1}} + \dfrac{1}{\overline{Z}_L} + \dfrac{1}{\overline{Z}_{T2}}\right)} \tag{C3}$$

Also,

$$\bar{I}_{T1} = \frac{\overline{V}_{T1} - \overline{V}_L}{\overline{Z}_{T1}} \tag{C4}$$

And

$$\bar{I}_{T2} = \frac{\overline{V}_{T2} - \overline{V}_L}{\overline{Z}_{T2}} \tag{C5}$$

$$\overline{S}_{T1} = 3\times(\overline{V}_L \times I_{T1}^*) \tag{C6}$$

$$\overline{S}_{T2} = 3\times(\overline{V}_L \times I_{T2}^*) \tag{C7}$$

Assumptions made:

- Load Z_L is a fixed impedance load that gives 40MVA at 0.9 p.f. and nominal voltage.
- The resistance of the load is in parallel to its reactance.
- The transformer leakages reactance does not change with a change in tap position
- The transformer internal voltages are in phase

$$R = \frac{(22\times10^3)^2}{(40\times10^6)\times\cos(25.84)} = 13.44\,\Omega$$

$$X = \frac{(22\times10^3)^2}{(40\times10^6)\times\sin(25.84)} = 27.76\,j\,\Omega$$

$$Z = \frac{13.44 \times 27.76j}{13.44 + 27.76j} = 12.097\angle 25.84\,\Omega$$

From equation C3, C4, C5, C6 and C7 the following is obtained:

$$\overline{V}_L = 12.729\angle -4.93 \text{ kV}$$

$$\bar{I}_{T1} = 452.11\angle -0.917 \text{ A}$$

$$\bar{I}_{T1} = 698.1439\angle -49.64 \text{ A}$$

$$\overline{S}_{T1} = 17.22 + j1.208 \text{ MVA}$$

$$\overline{S}_{T1} = 18.94 + j18.75 \text{ MVA}$$

APPENDIX D: Testing the response of the relays to different Limitation Factor setting.

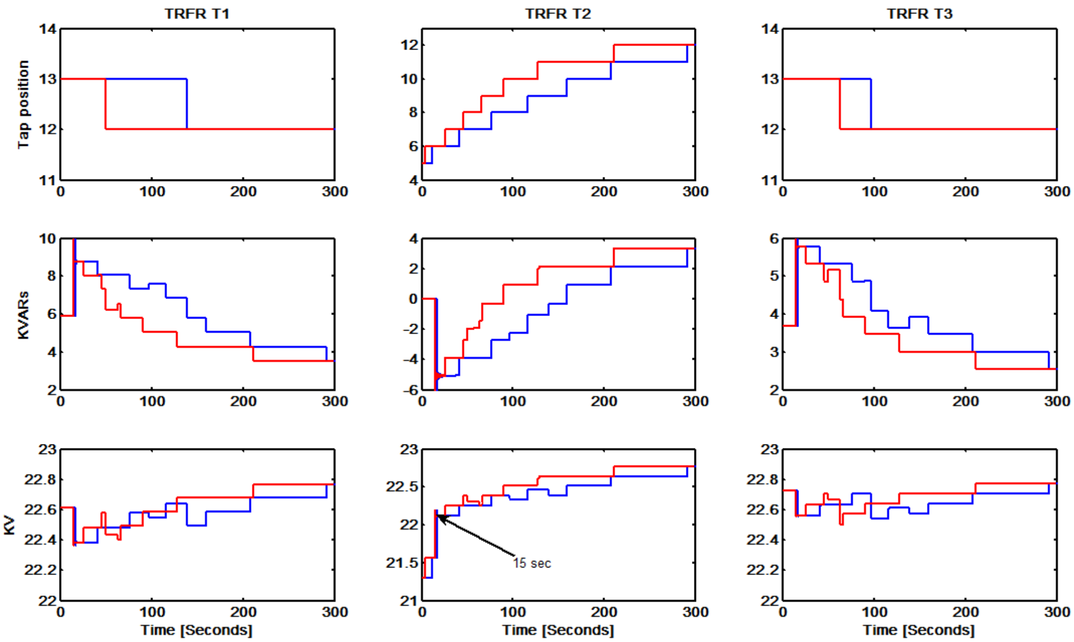

Figure D1: Real-time simulator testing of the Limitation Factor setting of the REG-D relays.

Figure D1 shows further comparative analysis of the results from Figure 30, in which the responses of the system for two particular Limitation Factor settings (Limitation Factor settings of 2 and 5 from Figure 30) are replotted on the same axes. The responses of the relays with a Limitation Factor setting of 2 are shown in blue and those with Limitation Factor setting of 5 are shown in red.

It can be seen in Figure D1 that after 15 seconds the secondary voltages of all of the transformers are within the set voltage tolerances but the transformers still do not share the reactive power loading and thus continue to change tap positions in order to regulate the circulating currents that flow between them. Since the secondary *voltages* of the transformers are within their set tolerances from time t = 15 seconds onwards, it can be concluded that the dominant component of the combined error signal Y from this time onwards is the error signal Y_P from the output of the $\Delta\cos\varphi$ algorithm.

It can be seen in Figure D1 that when the Limitation Factor is set to its smallest value of 2, then the last tap change that transformer T2 performs in order to return the transformers to equal reactive power loading occurs at time t = 291.39 seconds; by contrast, when the Limitation Factor setting is set to 5 then the last tap change needed on transformer T2 before equal reactive power loading conditions are obtained takes place at time t = 211.12 seconds, which is considerably quicker than when the Limitation Factor setting is set to 2. This direct comparison of the regulators' performances from the time t = 15 seconds onwards (when the voltages are within regulative deviation) clearly demonstrates how the weighting (priority) of the $\Delta\cos\varphi$ algorithm can be influenced by means of the Limitation Factor setting.

APPENDIX E: Laboratory Test Setup of the Hardware REG-D relays

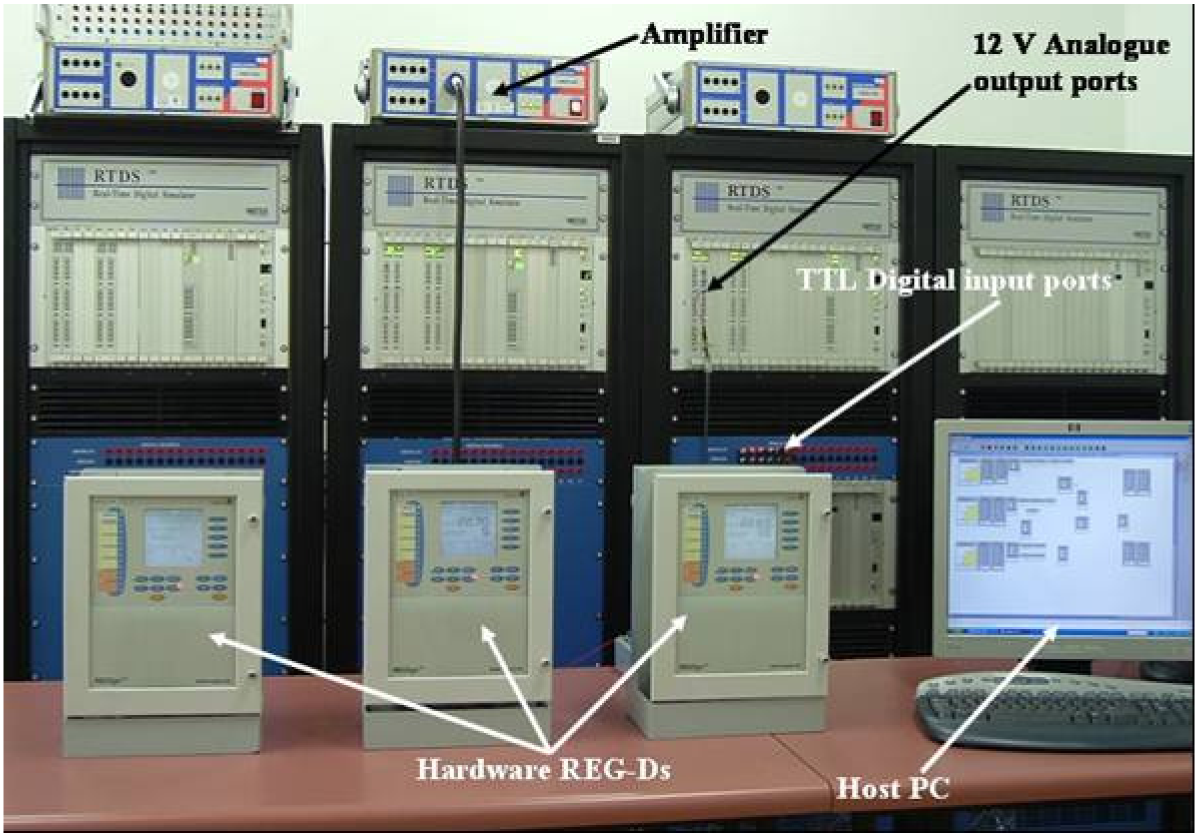

Photo E1: Real-time simulator testing of the hardware REG-D relays.

Photo E1 shows how the REG-D relays were setup in the laboratory for testing their performance in the system shown in Figure 27. The amplifier was used to amplify the system voltages and currents obtained from the RTDS to realistic network values. The user is able to run the simulation from Run Time interface shown in Photo E1 and is also able to interrogate the simulation by, for example, opening and closing breakers from the Run Time interface. The network voltages and currents can also be viewed by the user from the Run Time interface.

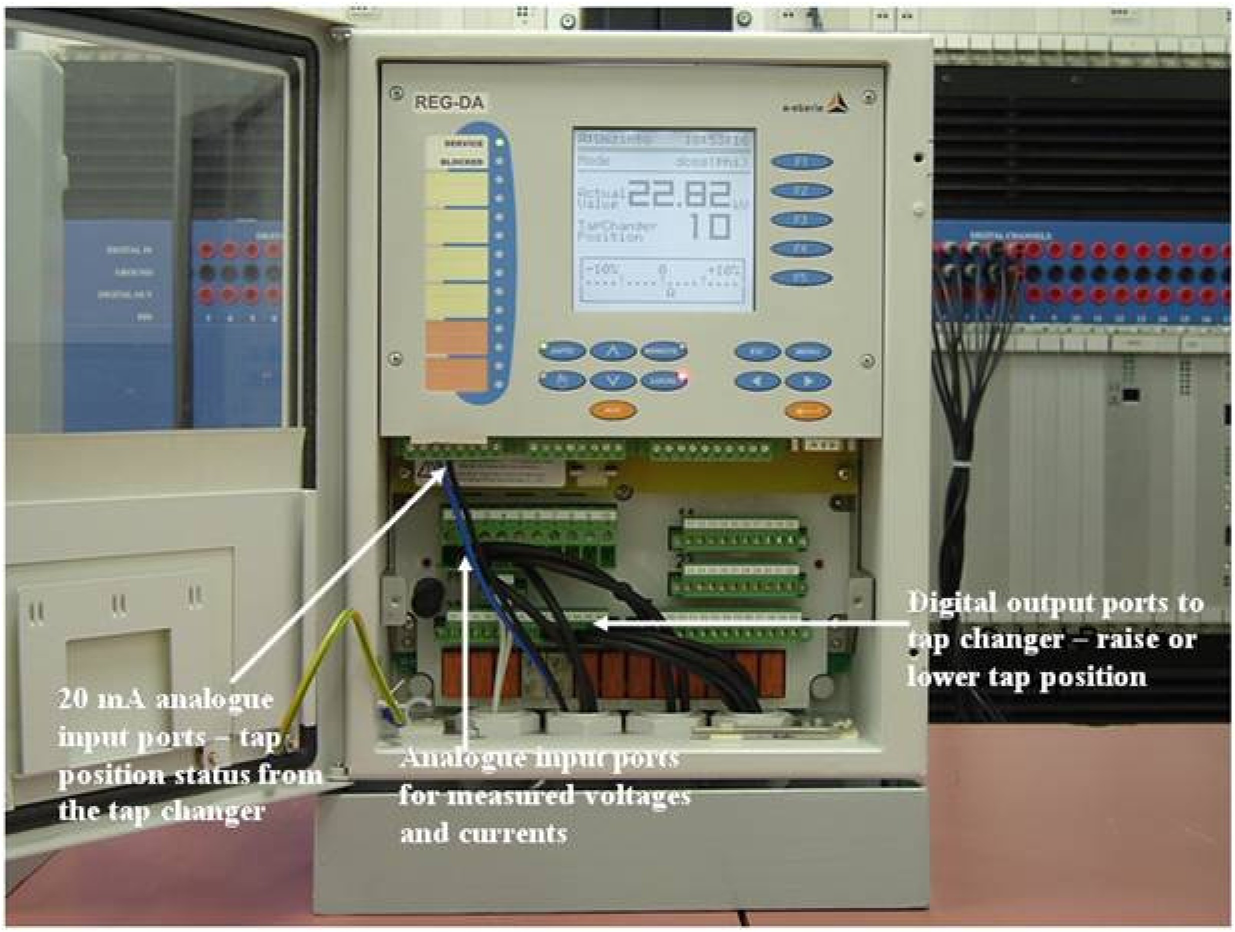

Photo E2: The front panel of the REG-D relay.

Photo E2 shows the front panel of a REG-D relay. From the photo it can be seen that the relay has 20 mA input ports that can be used as inputs for the tap position of the transformer and this signal would be received from the transformer tap changer. The transformer tap position can then be displayed on the LCD screen. The relay has analogue input ports where the measured network voltages and currents are inputs to the relay algorithms. The REG-D has digital output ports for issuing commands to either raise or lower the transformer tap position.

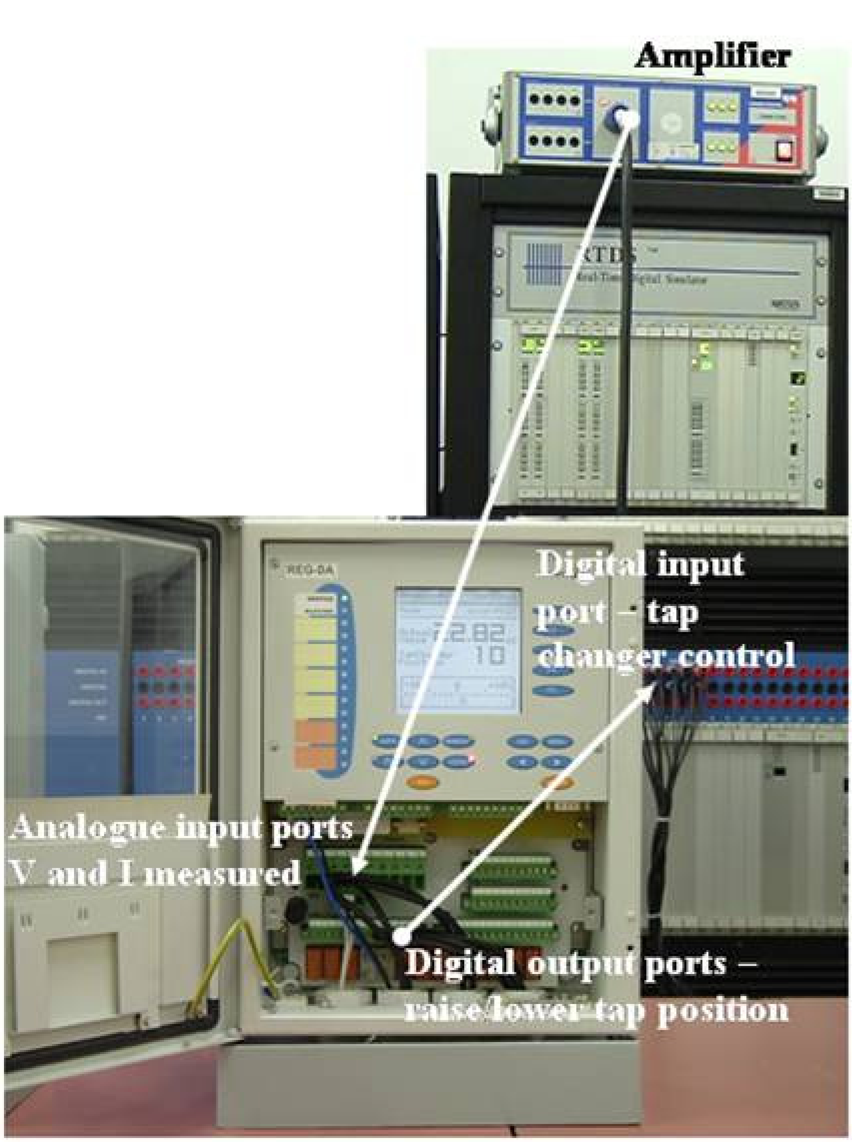

Photo E3: Hardware-in-loop control of a transformer taps using the REG-D relay.

There is a 16 Channel ± 10V analogue DDAC card situated at the back of the RTDS rack. During a simulation the real time simulator is able to output the measured network voltages and currents through this DDAC card. These voltages and currents are amplified to be representative of the actual network voltages and currents. The amplified network quantities are used as inputs to the relay through the relays' analogue input ports. The relay then processes these network quantities using its algorithms. The control command from the algorithms is sent to the tap changer through the relays digital output ports. The transformer tap changer receives the control command from the relays through the digital input ports of the RTDS as shown in Photo E3.

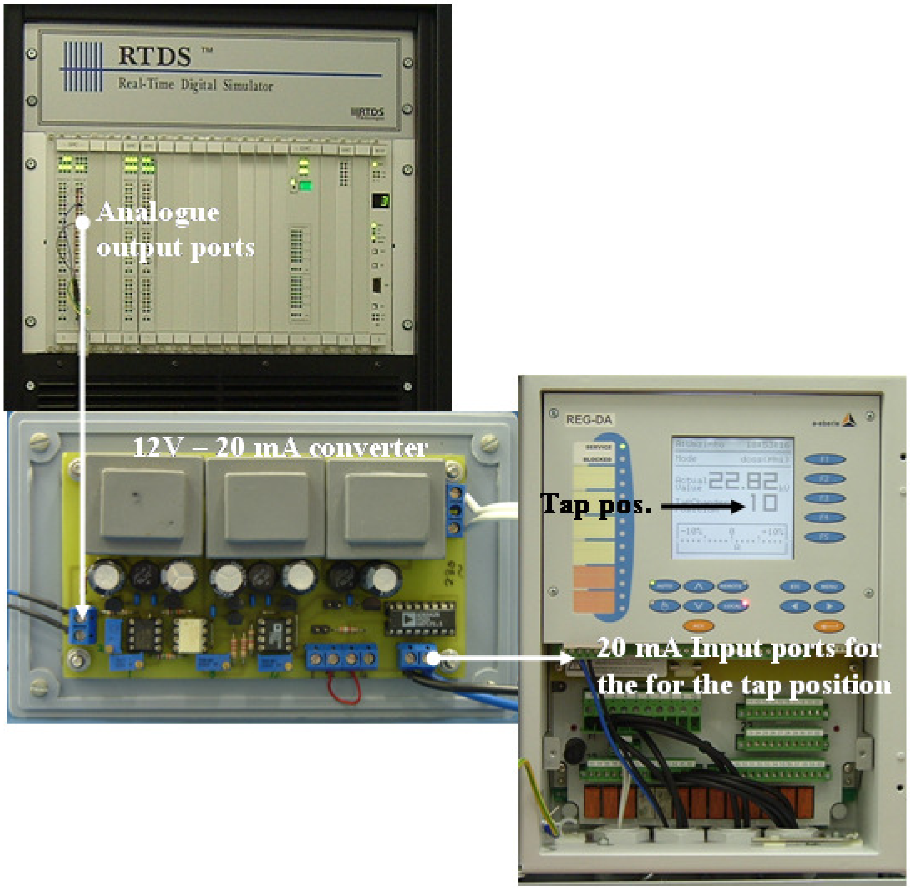

Photo E4: Displaying the transformer tap position on the REG-D relay.

The front panel of the RTDS rack has ± 12 V analogue output ports. During a simulation the real time simulator outputs a signal representative of the transformer tap position through one of these analogue output ports. This voltage signal is converted to a milliampere value. The relay then interprets this value as a tap position and the tap position of the transformer is then displayed on the LCD screen of the REG-D relay.