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# Distributed generation control using protection principles

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# Distributed Generation Control using Protection Principles

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## ABSTRACT

*In a distribution system, it is essential to maintain the voltage variation within a specified limit for satisfactory operation of connected customers' equipment. Normally, this goal is achieved by controlling the operation of compensating devices, such as load tap changing transformers, shunt capacitors, series capacitors, shunt reactors, and static VAr compensators. However, technical and regulatory developments are encouraging a greater number of small generator units, known as Distributed Generation (DG), and this has the potential to significantly affect voltage control systems. This paper presents an adaptive voltage control technique which incorporates DG systems into the voltage control system. The control scheme uses On-load Tap Changing Transformer (OLTC) and DG for voltage corrections, both are driven by advanced Line Drop Compensators (LDC). At the substation, the LDC is employed to control step up or step down decisions of the OLTC, while another LDC will be used at DG connection point to set DG parameters. Also, for a more cost-effective system, voltage control action coordination is proposed using magnitude grading and time grading. The control approach is tested on a modified distribution system with load variations that are stochastic in time and location. The results show that the integration of these magnitude grading and time grading, protection principles have considerably reduced the DG energy required to achieve the desired control.*

*Index Terms -- Distributed Generation, Power Distribution System, Voltage Control, On-load Tap Changing Transformer, Line Drop Compensator.*

## 1. INTRODUCTION

In the last few decades, customers have become increasingly more sensitive to the voltage violations outside the predefined limits. The National Electricity Market standards indicate that the range of voltages in distribution system should not exceed ± 5%. This is to ensure proper functions of connected electrical appliances, which are highly required by certain types of customers. This in return leads to an increased necessity for voltage management services. There are four methods which have been used widely to regulate distribution system voltage, including [1]:

a) On-load tap changing transformer (OLTC)
b) Capacitor bank (and/or reactor) switching
c) Synchronous and static compensators
d) Generating unit excitation systems

In most applications, the first two methods respond frequently after every short period to the voltage errors. The later ones, on the other hand, usually act continuously and rapidly to correct the system voltage within their capacity range.

Given that the distributed generation (DG) brings a considerable number of benefits with a more compact configuration and more competitive price, the wish to connect them into low voltage networks by distribution companies is increasing [2]. However, this tendency plus the growth of load demand and the uncertainties of load connection/disconnection have been contributing to the complexity of voltage regulation [3]. Traditional voltage control actions, in the absence of DG, depend much on the fact that the voltage profile decreases along the feeder from the substation to the remote end. In contrast, the integration of DG systems makes this characteristic no longer valid. Other possible difficulties involve the chance of interaction between different control devices and a DG or among several DGs. As a result, voltage control strategies need reconsideration [4].

Solutions for voltage control problem in the presence of DG have been reported in the literature recently. Authors in [5] have proposed an algorithm to control voltage with inverter-based DG for a uniformly distributed feeder model. The control method in [6] has been established by altering the automatic voltage control (AVC) relay target voltage based on the estimated maximum and minimum voltage nodes. In [7], an Artificial Neural Network has been applied to design the settings of AVC relay for OLTC control purposes. Mogos *et al.* have presented a voltage regulation system for electronic interfaced grid-connected DG based on active and reactive power control [8]. Authors in [9] have presented a nested evolutionary programming approach for optimising the voltage control variables, such as voltage reference, tap position, etc.

This paper introduces a new voltage control scheme for the presence of OLTC and DG as primary system voltage regulators. Both OLTC and DG are driven by an advanced line drop compensator (LDC), which is expected to provide good overall performance and viable running cost. Moreover, the magnitude and time grading principles in protection system have been adapted to avoid the risk of interaction between OLTC and DG, as well as to utilise the capacity of taps. Simulations are conducted over a small period of time with consideration of load dynamics to show the effectiveness of the method.

## 2. OPERATING PRINCIPLES OF LDC

The operation of OLTC and DG usually can be obtained in a simple way by controlling the local voltage at their common coupling points. Due to the high diversity in location and demand of customers with respect to time, the voltage references of these regulators need to be set relatively high to guarantee no under-voltage problems in the system. This is sometimes very costly since DG may overrun at some stages. Moreover, unnecessary taps and DG switching are more likely to happen. To overcome these challenges, the LDC has been proved to be very promising. As LDC is more sensitive to the changes of load and system voltage, it is able to predict voltage drop more effectively, and thus, reduce DG running time if possible. In addition, LDC allows a simpler and more accurate tuning process for voltage control.

### 2.1. CONVENTIONAL LDC

It is quite common in distribution system that the aimed point for voltage regulation is neither at the secondary side of substation transformer nor DG's location, but at some remote load centre. Ideally, the best way for voltage problem solving in this case would be using the actual voltage at that point as the feedback to the controller [10]. However, this is not a preferred solution to the distribution companies as it requires extra measurement and communication systems. LDC, on the contrary, uses the local measurements of voltage and current to predict voltage at remote load with acceptable discrepancy. Besides the local voltage and current, voltage prediction of conventional LDC also depends on the internal coefficient settings of LDC, R and X. The R and X are usually adjusted to reflect the line resistance and reactance, thus make it possible for LDC to give an indication of the remote voltage. The design of R and X has been discussed in [10-12].

### 2.2. ADVANCED LDC

In practice, it is sometimes very challenging to select an effective R and X as the load change is unpredictable. Also, the tap changing operation and the inclusion of DG systems have made this process even more complicated [13]. In this section, an advanced LDC which predicts remote end voltage only by using the local voltage and current measurements is proposed. The LDC works based on the assumption that the line current drops linearly from measurement point to the end of the feeder. Thus, the estimated current $x$ kilometres from the substation can be written as:

$$I(x) = -\frac{I_d}{(l-d)}x + I_d \tag{1}$$

where $l$ and $d$ are the distances in km from the remote end and regulation point to the substation, $I_d$ is the measured current at $d$.

Voltage prediction at the remote end is determined by subtracting the estimated voltage drop from the measured voltage at regulation point $d$:

$$V_{pr} = V_d - \int_{x=d}^{l} zI(x) \tag{2}$$

Eq.(2) can be simplified as,

$$V_{pr} = V_d - (z/2)I_d(l-d) \tag{3}$$

where $V_d$ is the measured voltage at $d$ and $z$ is line impedance per unit length.

The advanced LDC has eliminated the possibility of inadequate voltage prediction caused by poor design of LDC internal settings. Therefore, more accurate prediction with higher confidence can be obtained.

## 3. PROPOSED VOLTAGE CONTROL ALGORITHM

In this paper, the mission of maintaining system voltage within the specified limits is achieved by controlling tap change of OLTC and output current from a single DG. Each voltage regulator is equipped by an advanced LDC and they are both responsible for looking after the remote end voltage. Real-time practice of voltage control system also requires taking into account temporary voltage drop circumstances due to short term load variations. Such situations usually do not hold for long time and are the system is expected to automatically recover. Therefore, any tap change or DG operation in response to them is undesired by utilities due to wear of contacts. This problem, though, can be easily solved by inserting a time delay into the regulators. First tap or DG adjustment takes place after a time delay, then responds instantly to the next. The delay is recommended to be long enough to overcome any unnecessary responses. To improve the performance of the control system, a time delay and a voltage reference setting is integrated for each regulator. This is an imitation of the grading principles in protection system, which are known as time grading and magnitude grading. The grading process will be discussed in detail later on.

### 3.1. VOLTAGE CONTROL BY OLTC

The status of OLTC can be categorised into three types: do nothing, tap up, and tap down. These statuses are coded as 0, +1, and -1, respectively, and determined by following rules (with $V_{ref1}$ is the reference voltage and $V_{pr1}$ is the estimated remote voltage of OLTC controller):

1) Default status of OLTC is 0
2) If $V_{pr1} < V_{ref1}$ – dead band: current status is +1
3) If $V_{pr1} > V_{ref1}$ + dead band: current status is -1
4) Otherwise, current status is 0

A counter is set up in the controller with default value of zero to make sure tap changes for permanent voltage problems only. The control algorithm of OLTC can be summarised as below (for $t > t + 1$):

Step 1: Determine the current status of OLTC at time $t$ using LDC and local measurements at transformer point. If the status is +1 or -1, go to Step 2. Otherwise, go to Step 6.

Step 2: Does the status of OLTC remain the same as that at time *t*-1? If yes, increase the counter by 1 and go to Step 3. If no, go to Step 5.
Step 3: Has the counter equals or greater than the delay time of OLTC? If yes, go to Step 4. If no, go to Step 6.
Step 4: Has the OLTC exceeded its limit? If yes, go to Step 6. If no, tap up (as status is +1) or tap down (as status is -1)
Step 5: Reset counter to zero.
Step 6: $t = t + 1$ and go to Step 1.

### 3.2. VOLTAGE CONTROL BY DG

The DG control methodology shares some similarities of the OLTC's. Decision making of DG operation is also driven by a variable called current status and counter is employed to trigger DG action only in actual need. Default values of both the current status and the counter are zero. Obviously, these variables work independently from those of the OLTC.

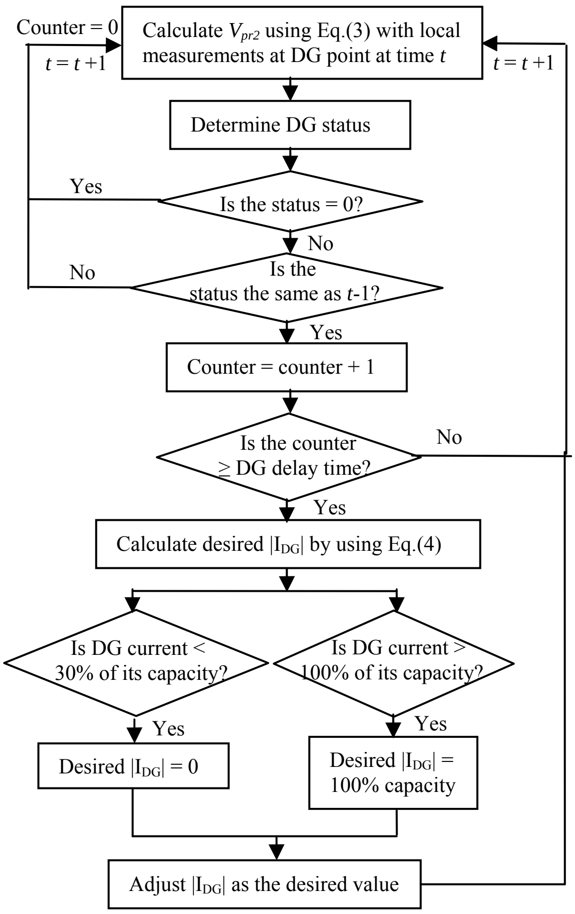


Figure 1: DG controller's algorithm

Current status of DG is defined as follows (with $V_{ref2}$ is the reference voltage and $V_{pr2}$ is the estimated remote voltage of DG controller):

1) If $V_{pr2} < V_{ref2}$ – lower tolerance: current status is +1
2) If $V_{pr2} > V_{ref2}$ + upper tolerance: current status is -1
3) Otherwise, current status is 0

Lower tolerance is substantially smaller than the upper tolerance. This is due to the fact that reference voltage is usually set closer to the lower voltage limit to keep DG from over running. Thus, further voltage rise from the reference is tolerable while further voltage drop from it is hardly accepted.

The proportional and integral controller type is used for DG. Voltage error given by the LDC plus some level of tolerance is referred to as feedback signal for the controller. The DG, after receiving feedback signal, will adjust its output current to correct the voltage as,

$$\Delta|I_{DG}| = K_P\left(|V_{ref2}| - |V_{pr2}| + \varepsilon\right) \quad (4)$$

In this case, DG has been modelled as a constant current source. Its phase angle is determined such that the DG would always give maximum voltage change in the feeder [14]. Also for efficient and economic reasons, it is assumed that DG works only if its output current is greater than 30% of the DG capacity and DG will be switched of otherwise. The control logic of DG is described in the flowchart of Fig.1.

Since both OLTC and DG are working towards the same aim of correcting the remote voltage, the two controllers may experience some interactions. These interactions, nevertheless, could be minimised by setting $V_{ref1}$ considerably higher than $V_{ref2}$. By doing this way, it is unlikely that DG has to have substantial run time when the OLTC is not yet saturated, and thus reducing the chance of interaction. The design of voltage reference level and delay time in the controllers were in fact adapted from the magnitude grading and time grading characteristics, respectively, of the protection system. The employment of these principles is very helpful in improving the control scheme by many ways, such as,

- Utilised the capacity of the OLTC, which is considered as a less expensive voltage regulation method. Therefore, reducing the running cost of DG.
- Control actions of OLTC and DG only take place in case of permanent voltage problems.
- Minimised the risk of interactions among controllers.

## 4. TEST SYSTEM AND LOAD DATA

A test system was constructed from real distribution network data. This is a 69 node 11 kV feeder model, with one MV/LV OLTC connected the feeder to the substation, and one DG at node 65, as shown in Fig.2. Distance between any two nodes is assumed to be constant.

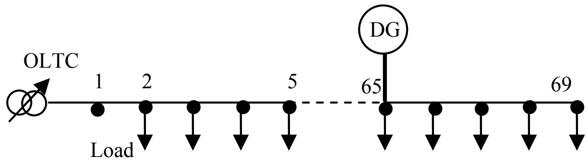


Figure 2: Test system model

The OLTC has the tap ratio of 1:a, where a varies between 0.95 and 1.10. The tap step is 1.25% and the delay time of first tap is 4 seconds. The LDC's dead band used in the OLTC is 1%. The LDC used for the DG has upper tolerance of 0.5% and lower tolerance of 0.2%.

A simulation is carried out for 100 seconds with a time step of 1 second to demonstrate the effectiveness of the control method. The LDCs of OLTC and DG receive their local voltage and current measurements and predict the remote end voltage periodically. If the estimated remote voltage is defined to be not safe within the limits, control action will happen. The test network is desired to operate within ±5% from the nominal voltage level.

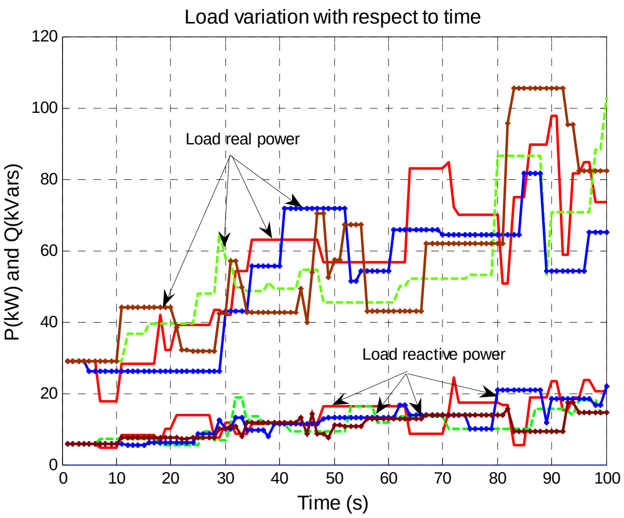


Figure 3: Load profiles at some selected customers

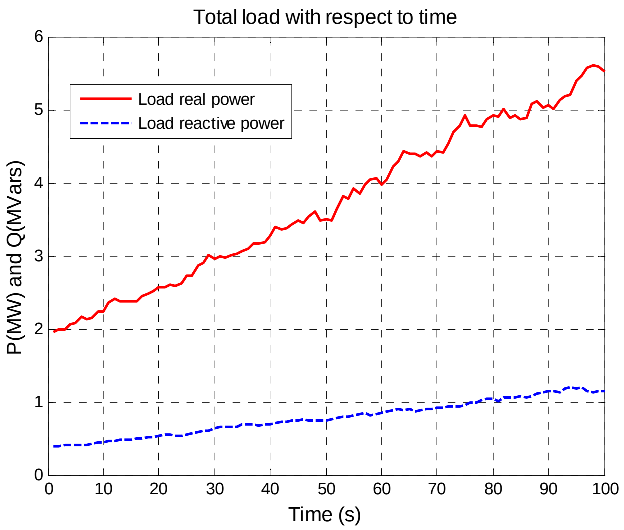


Figure 4: Total feeder active and reactive load profiles

A set of load data for 100 seconds was produced for the test, imitating the nature of load change, which is usually stochastic in time and location. Total feeder load increases from 2 MVA up to 6 MVA to represent transition from light loaded to heavily loaded situation. To represent the stochastic nature of loads, 20% of the busses, which were selected randomly from the set of 68 busses, to vary at time *t* from their load levels at time *t*-1. Load variations were calculated by adding a certain amount of variation (randomly up to 2.5% of the prior load level) and a correction factor such that the general increasing trend of load will be followed. Real and reactive power variations were independent from each other, thus, customer's power factor is not a constant value. The remaining 80% of customers maintain the same load as at time *t*-1. The active and reactive load profiles of four selected customers are shown in Fig.3, which illustrated the non-uniformly load characteristic of the test feeder. Total feeder load profile with respect to time is given in Fig.4. Total load in the examined period is 103.12 kWh.

## 5. RESULTS AND DISCUSSIONS

Simulations have been conducted in two cases: (1) DG has the delay time of 3 seconds for the first decision and then responds instantly; (2) DG is designed to respond at every instant to the voltage error signal. The voltage reference of LDC for the OLTC is 0.976 p.u. and for the DG is 0.956 p.u. Besides the purpose of maximising tap usage, the reference voltage of LDC at OLTC was set relatively high also because of its less effective voltage prediction. Due to the inclusion of DG as well as the characteristic of the LDC used (based on the linear current drop assumption), the further the LDC from the remote end, the less accurate the voltage prediction.

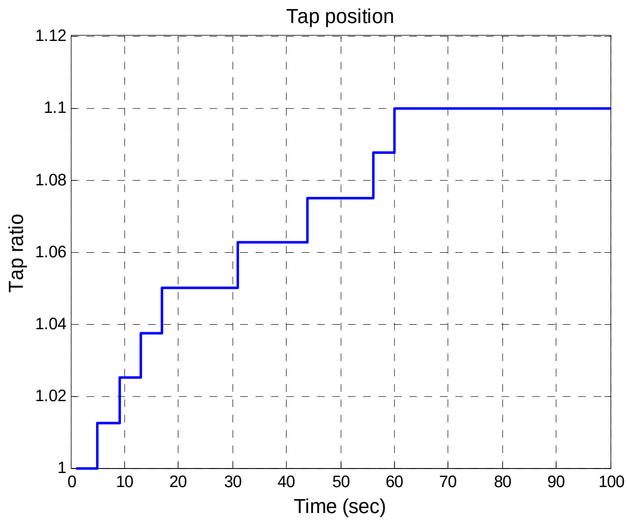


Figure 5: Tap position in case of delayed and non-delayed DG to support feeder load

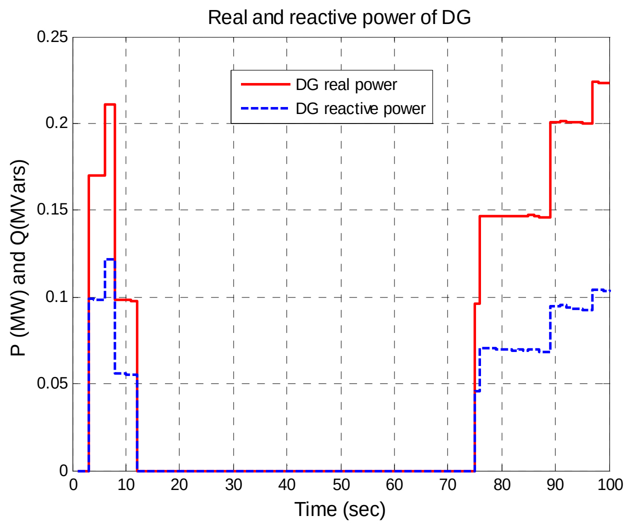


Figure 6: DG injection power with non-delayed DG

Fig.5 shows the tap position to control the voltage level, which remains the same for the delayed and instantaneous DG control cases. As the load increases, the tap ratio also increases until it reaches its saturated state. In Figs.6 and 7, the real and reactive injection power from DG in case 1 and case 2, respectively are shown. The ratio of the DG real and reactive power, as can be observed from these figures, is always kept constant at 1.78 for maximum voltage change effectiveness [14]. We can also see that because of the DG immediate reaction, the generator in case 1 is running more compared to case 2. As the result, a better voltage profile can be expected in case 1. The remote end voltage profiles without DG, with DG, and voltage predictions at two regulation points, for 2 cases, are illustrated graphically in Figs.8 and 9. The figures obviously indicate that smaller under-voltage time is achieved with the non-delayed DG. By using the control scheme, the DG is turned on to provide extra support to network voltage only in two scenarios, when the tap has not yet reached its desired level and when the tap is saturated. Otherwise, the voltage is mostly regulated by the OLTC. The remote voltage with and without DG in two cases also reveal that DG has made a considerable contribution to the control of system voltage.

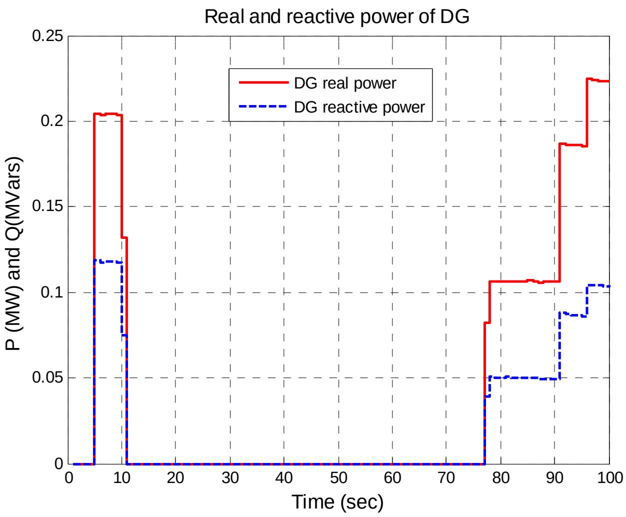

Figure 7: DG injection power with delayed DG

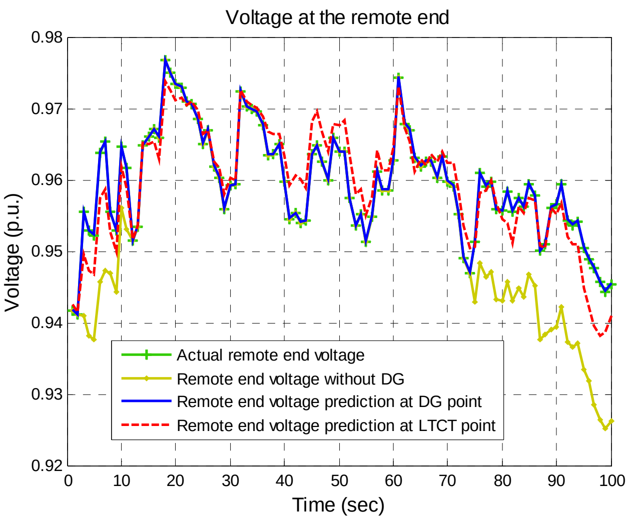

Figure 8: Remote end voltage with respect to time for the case of non-delayed DG

Table 1 provides the summary of the results in the two cases. In case 1, the non-delayed characteristic of DG makes it working harder, thus provides a better voltage profile with less percentage of customers suffering from under voltage problem compared to case 2. However, the running cost of this system is also more expensive. Moreover, in several situations, the control scheme in case 1 may cause the DG to turn on more frequently than that of case 2. To certain types of DG, this will also raise the total operating cost of the system. As we can obviously be aware, the best control scheme needs to be carefully selected in trade-off among the priorities. If it is very important to maintain the network voltage within the specification, a non-delayed DG will perform better. Otherwise, a DG with some time delay will be more suitable as an economic choice.

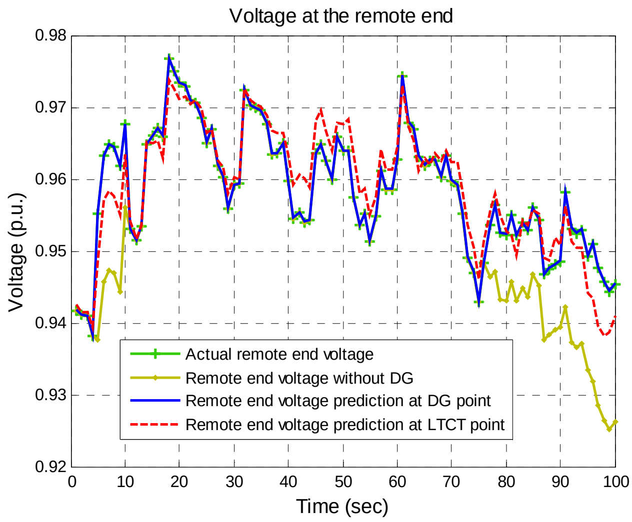

Figure 9: Remote end voltage with respect to time for the case of delayed DG

Table 1: Comparison of two control systems

| | **Case 1** | **Case 2** |
|---|---|---|
| RMS error in voltage prediction at OLTC point (μp.u.$^2$) | 1090 | 1051 |
| RMS error in voltage prediction at DG point (μp.u.$^2$) | 0.782 | 0.781 |
| Total customer minute under voltage (customer-minute) | 2.367 | 4.317 |
| Customer minute under voltage as percent of total time | 2.088% | 3.809% |
| Total DG working (kWh) | 1.618 | 1.297 |
| DG kWh as percent of total load | 1.569% | 1.258% |

It is seen from Table 1 that the RMS error in case 1 is higher than case 2. This can be explained by the fact that the reversed current flow from DG has an effect on the accuracy of voltage prediction. As DG is working more in the first case, its errors are also higher. Furthermore, the RMS errors of the LDC at OLTC are considerably larger than that at the DG, which is as expected.

As discussed earlier, it is actually simpler to control the regulators by using their local voltages. However, this process may result in more expensive operation cost of the system. Another simulation has been carried out to verify the choice of the LDC. Both OLTC and DG are set to be controlled by their local voltages. The reference voltages of two regulators have been adjusted such that the control scheme provides the same quality level to what we have archived using the LDCs (customer minutes under-voltage as fraction of total time is

3.809%). The results show that the total DG working in this case is 1.307 kWh, which is higher than the controller driven by the LDC (1.258 kWh). Even though this does not seem to be a huge difference, it is expected that the LDC would be much more beneficial if a longer run of the controller is examined. In addition, in reality, the lower uncertainty about the performance of the local-voltage controller usually results in a higher reserve margin i.e. high reference voltage setting. This means that the DG will work more often, as well as having a higher running cost.

## 6. CONCLUSIONS

This paper has introduced a voltage control system for using a OLTC and a single DG. Decisions for these regulators' control action have been made by using a modified LDC. This LDC managed to predict the voltage at a reasonable accuracy and without taking the risk of ineffective selection for the internal setting as in the case of conventional LDC. The proposed LDC is therefore more flexible and precise, especially in the presence of DG. The protection system's principles, which are magnitude grading and time grading, applied in this control scheme have greatly improved its performance by many ways. Not only the capacity of the tap is maximised, but also the interaction level between controllers is minimised. Moreover, the control system has lessened the unnecessary operation of the tap and DG, thus result in a less expensive running cost. Besides, no communication is required to run this voltage controller. The test results reveal that the network voltage has been improved in a by the control system. The analyses have been provided to demonstrate the benefits of LDC rather than the local-voltage control. Also, the comparison of delayed and instant DG is able to help the control engineer in selecting the most suitable control system, to satisfy the utility and the customer's need.

## 7. ACKNOWLEDGEMENTS

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