# Analysis and control of Shunt-Compensator for mitigating Unbalanced Voltages

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*Abstract*--**This paper presents the analysis and the control of shunt-compensator for improving unbalanced voltages of power distribution systems in Thailand. The shunt-compensator is connected to the low voltage level in power distribution system. The analysis detail and the design of shunt-compensator obtain by using the voltage vector control (mathematical model with the stationary reference frame and synchronous reference frames). The unbalanced voltages are identified by using positive and negative sequence detection that can be shown in the synchronous reference frame. This method also presents the decoupling control including feed-forward control to compensate both positive and negative sequence component of grid voltage. The power circuit of the shunt-compensator and the distribution network are modeled by Provincial Electricity Authority (PEA) of Thailand that is the same as worldwide standard of power distribution system. By using computer program, the simulation results showed the benefit and the performance of proposed methodology which obviously ensure the performance of shunt-compensator for mitigating the unbalanced voltages**.

*Index Terms*-- **Shunt-compensator, synchronous reference frames, faults, unbalance and decoupled control.**

## I. INTRODUCTION

UNBALANCED voltages are the power quality related to the problem of industrial process sector such as semi conductor plant and physical industrials [1], The unbalanced voltages are caused by remote faults, step-up large loads and capacitor and transformer energizations. They affected the voltage at point of common coupling (PCC) where the facility connected to the grid. This has adverse the effects on the equipment connected to PCC and may damage the appliances equipment. The shunt-compensator, the commercial name is distribution static compensator, can be utilized to regulate voltage control, power factor, and stabilize power flow [2], [3]. It will inject voltage and current into power distribution systems at PCC when voltage disturbances occurred. The fast detection and control methods are needed for shunt-compensator.

As presented in the past, the attempt has been made on electric power quality problems and many solutions have been suggested to improve the power quality in electric distribution systems. There are many studies and implementations of shunt-compensator in literatures [1]-[8]. The topology development was developed by using voltage source converter (VSC) including LC filter and shunt-transformer. The shunt-compensator can work in either voltage mode or current control mode to control the amplitude and phase of injected voltage. In a voltage mode, the shunt-compensator is connected to the utility bus to maintain a balanced voltage at that bus, irrespective of unbalanced or distortion in either side of the bus. In this mode, the operation and maintenance of the shunt-compensator is the responsibility of the utility. Alternatively, in the current mode, the shunt-compensator compensates for any unbalance or distortion in the load. Ideally, it should draw a balanced current from the system, irrespective of any unbalance or harmonics in either the source or load. It is also assumed that the shunt-compensator is placed at utility bus or on customer premises. So, this paper, analysis models and simulation of shunt-compensator in distribution systems, proposes in voltage mode. The decoupling control methods with feed-forward control are complemented in the synchronous reference frame since it can eliminate steady state error and get fast responded.

The rest of the paper is organized as follows – the power distribution system model including unbalanced voltages description is given in Section II. Section III explains the shunt-compensator configuration that connects to power distribution system. Analysis of physical model of shunt-compensator is described in section IV. Section V shows the decoupling control methods with feed-forward control for active and reactive current control. The simulation results, that showed benefit and performance of shunt-compensator, are presented in Section VI. Finally, the conclusion and discussion are given in Section VII.

## II. UNBALANCED VOLTAGES

The problem of the grid voltage in power distribution system is unbalanced that caused by remote faults, capacitor and transformer energization and starting the large load into the grid [1]. To analysis the unbalanced voltage at PCC must use the best solution of computation machine and mathematical tool with the fast analytical method. The Fast Fourier Transform (FFT) method is selected for detection the voltage distortion. Fig. 1 shows the three types of unbalanced voltage that caused remote faults with the amplitude FFT

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detection method. The single line to ground fault is shown in Fig. 1(a) and transformer energization is shown in Fig. 1(b). As we known, the boundary of normal voltage is 0.9 – 1.1 p.u. The outside this region, the FFT detector will suddenly operate.

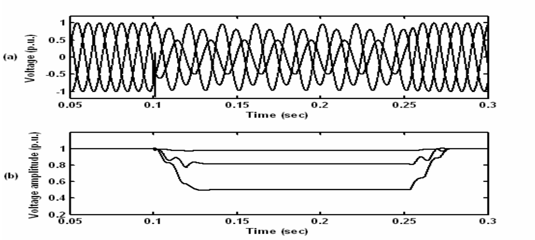

Fig. 1(a) Single line to ground fault in power distribution system.

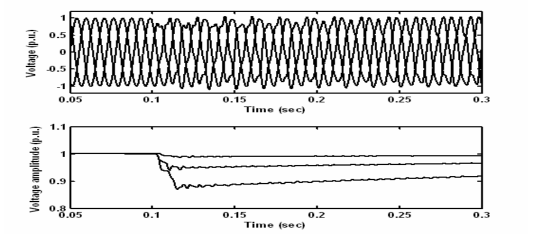

Fig. 1(b) Transformer energization in power distribution system.

The voltage of three-phase in an unbalanced system can be completely described in the steady state operation through symmetrically component voltages [7], namely positive sequence, negative sequence and zero sequence components. As shown in equation (1), it can be defined by using *a* parameter and power invariance method. Fig. 2 shows the phasor diagram of three types sequence component. It depends on what we define the direction of arrow of three phase voltage. The zero sequence component of three phase voltage has the same direction for all voltage and does not have in the balanced system. So, the zero sequence will be discussed more in this paper.

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{1}$$

if $a = -\frac{1}{2} + \frac{1}{2} j\sqrt{3}$

when $V_0$ = Zero sequence voltage
$V_1$ = Positive sequence voltage
$V_2$ = Negative sequence voltage

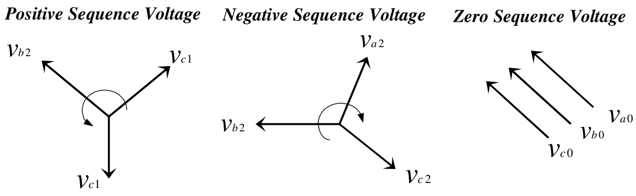

Fig. 2 Classification of three-phase voltage.

The FFT detection of unbalanced voltage is an important issue because it has to detect both amplitude and phase of three phase voltage. The waveform control receives the detection command to generate the reference command. Therefore, this is known as the FFT detection method.

### *A. Fast Fourier Transform (FFT) method*

The FFT is achieved through orthogonal decomposition of power system signal. In general, a trigonal orthogonal function set or exponential orthogonal function set is proposed to complete the Fourier series decomposition to a discrete periodic sequence. The real part, the imaginary voltage component is extracted normally from a time sequence over a fundamental frequency cycle it has been proposed to obtain through a FFT algorithm.

$$V(h) = \frac{1}{N}\sum_{n=1}^{N} v(n) e^{-i\frac{2\pi}{N}(n-1)h} \tag{2}$$

If $h = 1, 2, ...N$ and $h$ is component of harmonic
when $h = 1$ is fundamental frequency
$h = 0$ is dc. component

So voltage value of PQD can be changed algebraic equation (2) and to be shown in equation (3) to (6)

$$\begin{aligned} v(n) &= a_0 + \sum_{h=1}^{N}\left( a_h \cos\left[\frac{2\pi}{N}(n-1)h\right] + b_h \sin\left[\frac{2\pi}{N}(n-1)h\right]\right) \\ &= a_0 + \sum_{h=1}^{N} m_h \cos\left[\frac{2\pi}{N}(n-1)h + \varphi_h\right] \end{aligned} \tag{3}$$

coefficient of dc. component

$$a_0 = \frac{1}{N}\sum_{n=1}^{N} v(n) = V(0) \tag{4}$$

coefficient cosinusoidal component

$$a_h = V(h) + V(-h) = \frac{2}{N}\sum_{n=1}^{N} v(n)\cos\frac{2\pi}{N}(n-1)h \tag{5}$$

coefficient sinusoidal component

$$b_h = j(V(h) + V(-h)) = \frac{2}{N}\sum_{n=1}^{N} v(n)\sin\frac{2\pi}{N}(n-1)h \tag{6}$$

So can be find amplitude and phase of three phase voltage in equation (7) to (8)

$$m_h = \sqrt{a_h^2 + b_h^2} \qquad \varphi_h = \arctan\left(-\frac{b_n}{a_n}\right) \tag{7}$$

$$\begin{aligned} m_1(k) = \frac{2}{N}\Bigg[\Bigg(\sum_{m=k-N+1}^{k} v(n)\cos\frac{2\pi}{N}(n-1+N-k)^2\Bigg)\Bigg] \\ + \Bigg(\sum_{m=k-N+1}^{k} v(n)\cos\frac{2\pi}{N}(n-1+N-k)^2\Bigg)^{\frac{1}{2}} \end{aligned} \tag{8}$$

when $k \geq N$ and $1 \leq k < N$ so $m_1(k) = m_1(N)$

## III. CONFIGURATION OF SHUNT-COMPENSATOR

As maintained on previous section, the compensator is the shunt-connected device on power distribution system which is to dynamically inject a voltage and current of desired amplitude, frequency and phase into PCC. The basic functions are fast switching and current/voltage injection for correcting anomalies in supply voltage or load current. The typical configuration of shunt-compensator consists of voltage source inverter(considering on multilevel VSC because it can reduce the shunt transformer sizing and filter sizing), DC-link capacitor, DC-link resistor, shunt-transformer, detection unit and voltage control unit, as shown in Fig. 3.

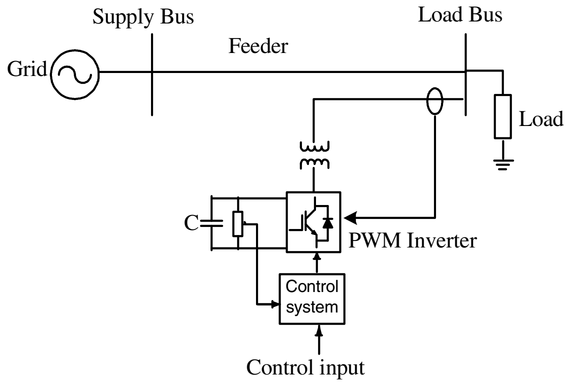

Fig.3. The configuration of Shunt-compensator connected distribution system.

The specifications of shunt compensation are presented in Table I. The load of this system defines as the unbalanced impedance and remote fault. The size of shunt-compensator is designed to support the unbalanced voltage about 1 second as the definition of IEEE 1159 standard for unbalanced voltage compensation. So, it can calculate the size of DC-link capacitor about 4 mF [8]. The long compensation time will get the large capacitor size.

TABLE I
SYSTEM PARAMETERS

| System Quantities | Values |
|---|---|
| System Voltage Level | 220/380 V |
| System frequency | 50 Hz |
| Load in p.u. | Impedance 0.2+1.5i, 2.55+1.25i and 1.0+2.3i in phases a, b and c respectively |
| Boost transformer in p.u. | Transformer leakage reactance 0.2<br>Rf+ jωLf = 0+2i |
| R and L filer | 0.01 and 2 mH |
| DC-link Capacitor | 4 mF |
| DC-link Resistor | 0.01 Ω |
| Switching frequency | 1050 Hz |
| Sample Time | 1 µs |

The system-parameters of power distribution system and shunt-compensator must be correctly calculated because all values will be used to find the control parameters for the next section. The configuration of the system will model into the computational tool on the computer to show the benefit and the performance. So, we will transfer all values to the same standard and in per unit (p.u.). Next section will present the mathematical model of shunt compensator by using synchronous reference frame that will be easily for understand the configuration of system.

## IV. MATHEMATICAL MODEL OF SHUNT-COMPENSATOR

The shunt-compensator and the sensitive load are connected at PCC as shown in Fig. 3. To analysis the system, we have to assume the unbalanced load and shunt-compensator to be ideal. So, the equivalent circuit of shunt-compensator can be written as shown on Fig. 4. The output voltage of voltage source inverter is defined as $V_{inv}$, The resistor and inductor filter are defined as $R_f$ and $L_f$, respectively. The grid voltage, $V_{grid}$, is the voltage at PCC. On Fig. 4 can also transfer to algebraic equation as shown in equation (9) to (11) for creating the shunt-compensator mathematical model. The model is defined from the stationary to synchronous reference frame[9].

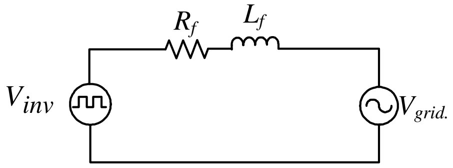

Fig. 4. Equivalent circuit of shun-compensator.

when $V_{inv}$ is inverter voltage

$V_{grid}$ is voltage in power system and voltage at PCC

$$L\frac{di}{dt}+R_f\cdot i=V_{in}v-V_g \tag{9}$$

Stationary reference frame to synchronous reference frame

$$\begin{bmatrix} V_\alpha \\ \hline V_\beta \end{bmatrix}=\sqrt{\tfrac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} V_d \\ \hline V_q \end{bmatrix}=\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} V_\alpha \\ \hline V_\beta \end{bmatrix} \tag{11}$$

From Equation (9) can be transferred dqo model by using Park's Transformation in equation (10) to (11).

$$\begin{aligned} &L_f\left[\frac{d}{dt}\left(i_d+ji_q\right)+j\omega\left(i_d+ji_q\right)\right]+R_f\left(i_d+ji_q\right)\\ &=\left(V_{in}v_d+jV_{in}v_q\right)-\left(V_gd+jV_gq\right) \end{aligned} \tag{12}$$

Then separated equation (12) can be algebraic equation of dqo- axis. Which d-axis as shown equation (13), q-axis in equation (14) and o-axis equation (15).

$$L_f\frac{d}{dt}i_d-L_f\omega\cdot i_q+R_f\cdot i_d=V_{in}v_d-V_gd \tag{13}$$

$$L_f\frac{d}{dt}i_q-L_f\omega\cdot i_d+R_f\cdot i_q=V_{in}v_q-V_gq \tag{14}$$

$$L_f\frac{d}{dt}i_o+R_f\cdot i_o=V_{in}v_o-V_go \tag{15}$$

Fine current in dqo-axis from equation (10) to (12) as shown equation (16) to (18)

$$id=\frac{1}{L_f\cdot s}\left[V_{in}v_d-V_gd+L_f\omega\cdot i_q-R_f\cdot i_d\right] \tag{16}$$

$$iq=\frac{1}{L_f\cdot s}\left[V_{in}v_q-V_gq+L_f\omega\cdot i_d-R_f\cdot i_q\right] \tag{17}$$

$$i_O=\frac{1}{L_f\cdot s}\left[V_{in}vo-V_go-R_f\cdot i_o\right] \tag{18}$$

and equation (16)-(18) can be modeled in the block diagram as shown in Fig. 5.

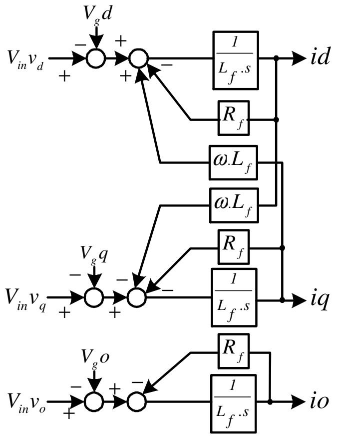

Fig. 5. Mathematical Model of Shunt-Compensator.

## V. CONTROL STRATEGY OF SHUNT-COMPENSATOR

In this section, the control strategy is presented by the decoupling voltage control including feed-forward voltage control scheme. The positive and negative sequence components of PCC voltage are detected and classified before sending into the control unit. The voltage control inside the block will be controlled both amplitude and phase for the desired voltage components discussed. The decoupling control is control strategy that applied to voltage source converter where are used in ac motor drive and continuous ac power supplies. The objective is to produce a sinusoidal ac output whose magnitude and frequency can be controlled. The decoupling control has been implemented in the synchronous reference frame because the synchronous frame controller can eliminate steady state error and has fast transient response Cross-coupling on dq and o components are shown in Fig. 7.

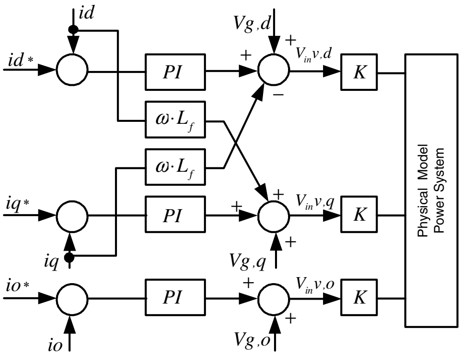

Fig. 7. Mathematical model of decoupling control.

The feed-forward component as shown in Fig.7 is the scheme that used eliminate the initiate sample value and to cancel the zero value of the electrical components. The PI regulators, namely $K_p$ and $K_i$ [10], are designed to keep the stability margin of the entire system by getting the eigen values on the left hand side of the S-plane. The DC-Link voltage must be controlled to keep the constant DC voltage that used for generating the desired voltage component of shunt compensator. The benefit and performance are given in the next section.

## VI. SIMULATION RESULTS

To verify our system, the system parameter is in Table I, starts with taking double line-to-ground fault at time 0.04 sec to phase A and B. Therefore, the amplitude of grid voltage is reduced at phase A and B as shown in Fig.8, but phase C does not change at 1 p.u. In dq component, the grid voltages also decrease the amplitude as shown in Fig.9. This system can detect the sequence component both positive and negative. During the fault, the shunt-compensator injects the currents to PCC as shown in Fig. 10 and Fig. 11 for dq component. This system compensates the balance voltage of PCC as shown in Fig.12.

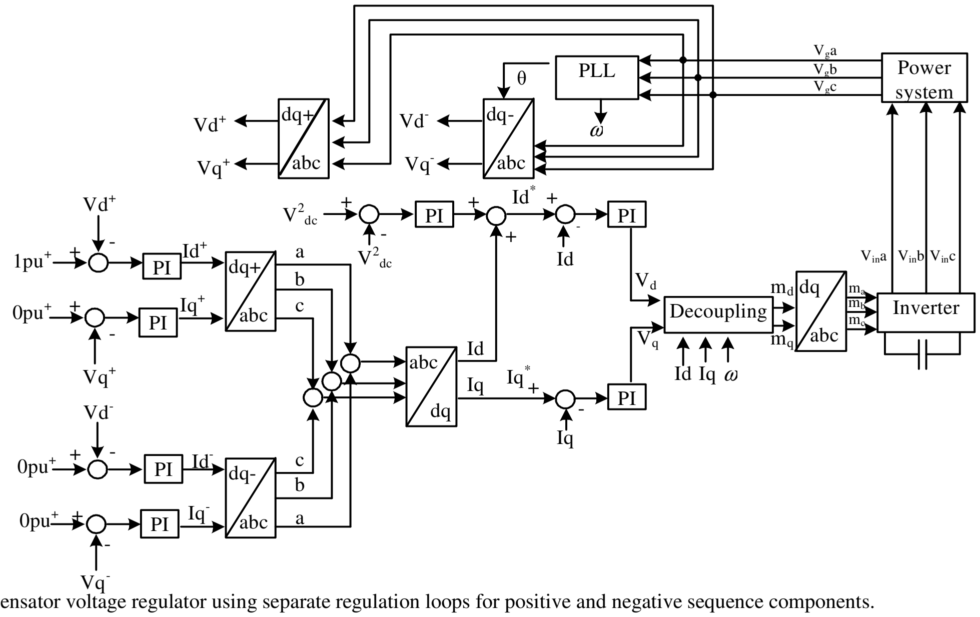

Fig. 6. Shunt-compensator voltage regulator using separate regulation loops for positive and negative sequence components.

## VII. CONCLUSION

The analysis and the control of shunt-compensator for mitigating unbalanced voltages are presented with the good performance. The responses show that shunt-compensator is able to provide opposite unbalance. It is hoped that the proposed shunt-compensator will be quite useful in a number of applications like sensitive load, isolated and remote micro grid power system where grid connected supply is not readily available. The unbalanced voltage that consists of positive and negative component can also mitigate by using shunt-compensator which the best decoupling vector control and feed-forward control.

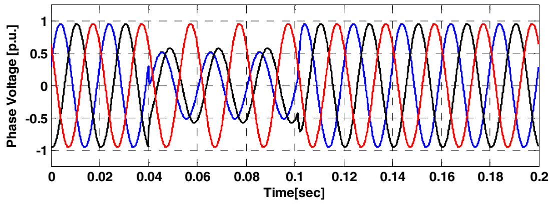

Fig. 8. Simulated three-phase grid voltage during unbalanced voltage sag.

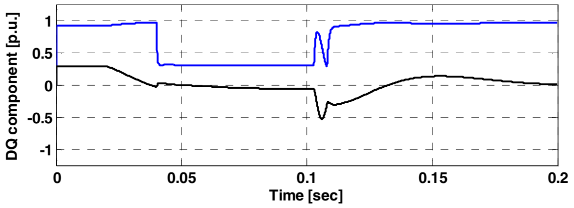

Fig. 9. dq-component of grid voltage.

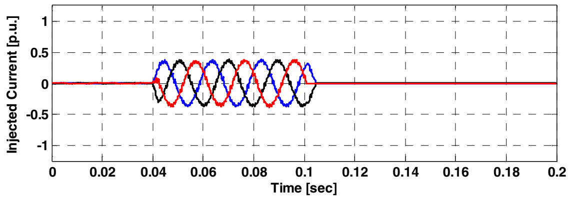

Fig. 10. Injected Current of Shunt-compensator.

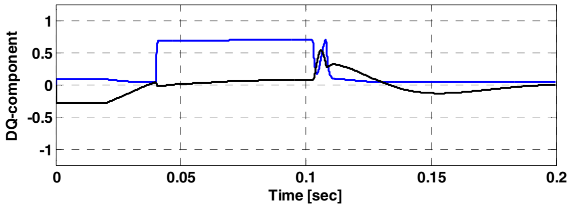

Fig. 11. Command of dq-component of grid voltage.

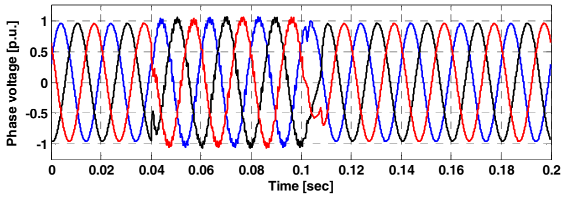

Fig. 12. Compensated voltage waveform at PCC References

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## IX. BIOGRAPHY

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