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Mitigation of supply voltage disturbances with a load voltage-controlled inverter

Hanny H. Tumbelaka*

Department of Electrical Engineering, Faculty of Industrial Engineering, Petra Christian University, Surabaya 60236, Indonesia

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Abstract

The three-phase four-wire Voltage Controlled Voltage Source Inverter (VC-VSI) is proposed as a multi-function voltage compensator for supply voltage disturbances to improve the load voltage quality. The VC-VSI is positioned in series between the disturbed source and sensitive loads. The VC-VSI works to immediately control the load voltage instead of its output voltage. The control process takes place in the *dq0* reference frame supported by a PI controller, since it is easy to build reference signals in the DC quantity. The VC-VSI successfully creates a three-phase compensation voltage instantaneously so that the load voltage is sinusoidal, balanced and constant at the nominal value. The VC-VSI has been modeled and simulated in PSIM simulation program to verify the proposed concept. The test results showed that the VC-VSI performed well as the voltage disturbance compensator, by retaining insignificant mismatch of ± 0.5% and low THD of the load voltage of 1.02%.

Keywords: Voltage sag/swell, Harmonic voltage, Unbalanced voltage, Voltage compensator

1. Introduction

An AC voltage supply usually encounters disturbances in a long or short duration such as interruption, voltage fluctuation, under- and over-voltage, distortion and unbalance [1, 2]. The disturbances could come from electric loads or electric network faults. Non-linear loads produce harmonics that would distort supply voltage. A short circuit or starting of a heavy load could cause voltage sag. As a result, electric loads, especially, sensitive or critical loads which are attached to the disturbed supply, may not work properly. Sensitive/critical loads need high-quality supply voltages, which must be balanced, sinusoidal and constant at the nominal value.

In general, customers install a back-up power supply such as a diesel generator set to eliminate interruptions/outages. While for voltage surge or spike problems, a surge protector such as transient voltage surge suppressor (TVSS) provides the simplest structure to clamp excessive transient/surge voltage to a safe level [2]. However, customers still need to handle short/long-duration voltage fluctuations, voltage distortion, and voltage unbalance, which may happen more frequent than complete interruption.

To mitigate those problems and provide sensitive loads with high-quality supply voltages, an alternative approach is to coordinate the control system in distribution networks and in local loads to maintain system voltages within specified values [3, 4]. It can use an on-load tap changer (OLTC) of the main transformer in the distribution network, while in local loads, the distributed generation units (DGU) such as a Photovoltaic generator provide finely control of the system voltage. An advanced static var compensator (SVC) as well as a static synchonous compensator (STATCOM) can also be a potential option, especially for distributed generation systems based on renewable energy sources, to handle voltage sag by adjusting its reactive power output [2, 5]. The control strategy of the grid-connected Photovoltaic generation has been also developed to overcome temporary voltage fluctuations [6, 7]. However, for the simplest and straightforward mitigation method, a voltage compensator is usually inserted between the supply at the point of common coupling (PCC) and the load. So, the load voltage will be separated from the disrupted supply voltage. The examples of the voltage compensator are a ferroresonance transformer, an uninterruptible power supply (UPS) and motor-generator sets, which attempt to supply good quality load voltages. But they have limitations and can only be applied cost-effectively at low power ratings [5].

Other attractive voltage compensators are the dynamic voltage restorer (DVR) and the series active power filter (SAPF). In this case, the compensator generates voltages that oppose the disturbance voltages. DVR is mostly used to eliminate voltage sag to the loads. DVR is a Voltage Source Inverter (VSI), which is mounted in series between the PCC and the electric loads using a matching transformer. DVR will maintain the load voltage at the nominal value by countering for the voltage deviation (ΔV) detected at the PCC [8-11]. Extensive efforts have been done to study DVR [12, 13]. DVR is also used in the hybrid PV-Wind Turbine power systems to improve the power quality and low voltage ride through (LVRT) capability [14]. SAPF is usually employed to block harmonic voltages from non-linear loads emerging to the PCC [15-17]. In the same way, SAPF could be used to reduce harmonic voltages from a distorted electric source to sensitive loads. Similar to DVR, SAPF is a VSI connected in series between the distorted source and electric loads using a matching transformer. The VSI will inject equal-but-opposite harmonic voltages of the distorted source. As a result, the loads will be supplied with a sinusoidal voltage waveform.

*Corresponding author.
Email address: tumbeh@petra.ac.id
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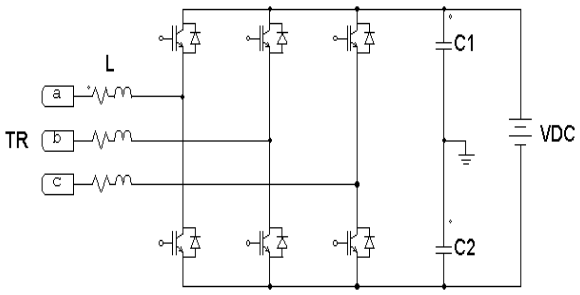

Figure 1 The three-phase four-wire VC-VSI power circuit

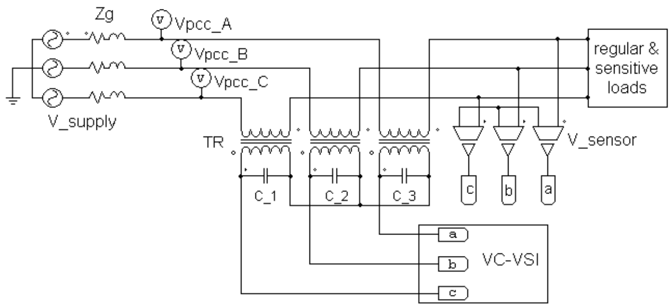

Figure 2 The position of the VC-VSI

In this paper, it is interesting to build a single multi-function apparatus to mitigate various kinds of supply voltage problems simultaneously by opposing any disturbance voltages. The aim of the voltage compensation is to obtain a high-quality load voltage. The multi-purpose voltage compensator for a three-phase three-wire system (a delta connection system) has been developed [18]. In this case, it uses a four-switch VSI as the main power circuit. However, the electrical system for residential and commercial buildings is a three-phase four-wire system, because their electric loads are generally operated as single phase system.

The conventional voltage compensator usually constructs a disturbance reference voltage, which is extracted from the PCC voltage. The transistors of the VC-VSI are switched to follow the reference voltage. Then, the VSI output voltage opposes the disturbance voltage so that the load voltage becomes balanced, sinusoidal and constant at the nominal value. Another control strategy is to add a current controller, which controls the VSI output current to improve the dynamic characteristics of the system [19]. This method needs more voltage sensors as well as current sensors, and control steps. In addition, it needs an effort to generate the disturbance signal, which may introduce errors and computational delays. Thus, it is a challenge to control the load voltage directly so that the compensation process becomes simple and fast.

This paper proposes a three-phase four-wire multi-purpose voltage compensator with a load-voltage controller for protecting sensitive or critical loads from disturbed supply voltages such as harmonics, sag/swell and unbalance. The expected results would be a high-quality three-phase load voltage, which is sinusoidal, balanced and constant at the nominal voltage level.

2. Materials and methods

2.1. Multi-Purpose compensator configuration

The proposed three-phase four-wire multi-purpose voltage compensator is a Voltage Source Inverter (VSI) with a DC source (e.g. battery) or an energy storage component at the DC side, and a small LC high-pass filter at the AC side to filter switching ripples. The DC bus voltage is kept constant [10, 16]. The VSI consists of six switches (i.e. six IGBTs with anti-parallel Diodes) and a split capacitor for grounded neutral connection as shown in Figure 1. The upper and lower switches of each half-bridge are switched on a complementary basis. The capacitor midpoint serves as a fourth wire.

For connection to an AC source, the VSI employs three single-phase matching transformers. The primary winding of the transformers is connected to the AC side (output) of the VSI. The secondary winding of the transformers is inserted in between the PCC and critical loads. Hence, the VSI behaves as series compensation (Figure 2). For a three-phase four-wire system, the transformer primary windings are configured in star/wye.

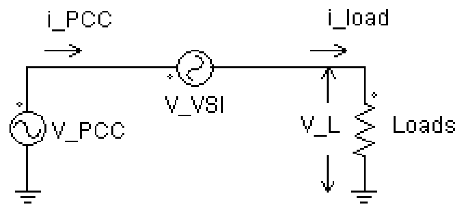

Figure 3 Mitigation process

2.2. Mitigation process

Figure 3 describes the mitigation process. The PCC voltage quality is influenced by power system environment. The PCC voltage consists of a three-phase balanced sinusoidal voltage at the nominal value (fundamental component = V_{Fund}) and disturbance voltages ($V_{Disturb}$). To reject the disturbance voltage, the inverter acts as a voltage-controlled VSI (VC-VSI). Its switching action will have a direct, immediate and predictable impact on the load voltage. The load voltage quality depends on the VC-VSI operating performance. To obtain a balanced and sinusoidal three-phase load voltage at the nominal value, a bipolar PWM controller is used to switch the VSI transistors such that the VSI produces a proper output voltage (V_{VSI}), which is equal but inverse to the disturbance voltage ($-V_{Disturb}$) according to Kirchhoff Voltage Law (KVL):

$$V_{Supply\,(PCC)} + V_{VSI} + V_{Load} = 0 \tag{1}$$

$$V_{Supply\,(PCC)} = V_{Fund} + V_{Disturb} \tag{2}$$

According to equations (1) and (2), it is better to focus on controlling V_{Load} to achieve the high-quality load voltage. A simple and precise control strategy is to regulate the load voltage immediately by tracking a high-quality AC reference voltage. Hence, the VC-VSI works to directly control the load voltage ($V_{Load,\,Ph\text{-}N}$) instead of its output voltage (V_{VSI}). For this purpose, the voltage sensors are positioned on the load side rather than on the PCC side and the VSI side. The load voltage is detected and directly controlled to follow a three-phase balanced sinusoidal reference waveform ($V_{REF,\,Ph\text{-}N}$). The amplitude of the reference waveform must be steady at the nominal level (e.g $220\sqrt{2}$ V). Its phase angle will be synchronized to the fundamental component of the PCC voltage (using a phase-lock-loop – PLL circuit) so that a phase jump will not happen during compensation [13, 20, 21]. For perfect tracking, the VC-VSI automatically generates compensation voltages (sag/swell, harmonic, unbalance voltages etc.) according to equations (1) and (2) without measuring the PCC voltage and determining the inverse disturbance voltage. Figure 4 depicts the block diagram of a direct load voltage controller. The controller uses the *abc*-to-*dq0* transformation and its inverse [11, 21, 22] to improve the tracking process, as follows:

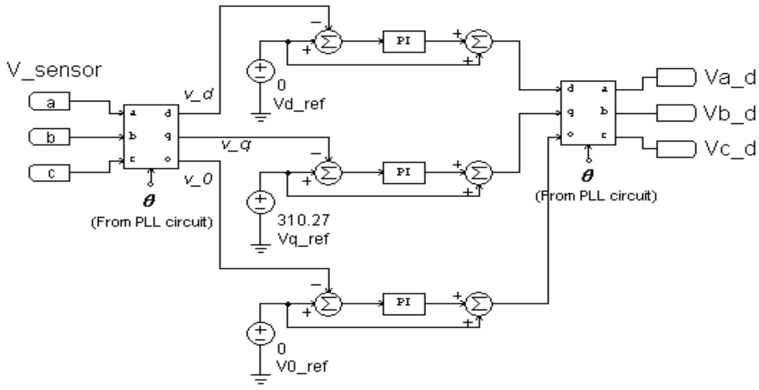

Figure 4 A direct load voltage controller in dq0 reference frame in PSIM program

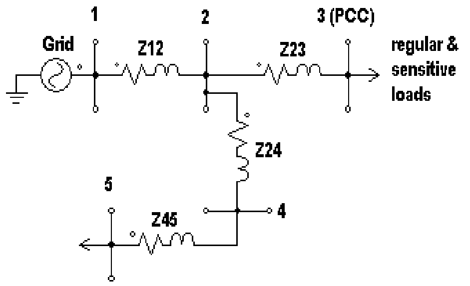

Figure 5 A typical electric network under study [7]

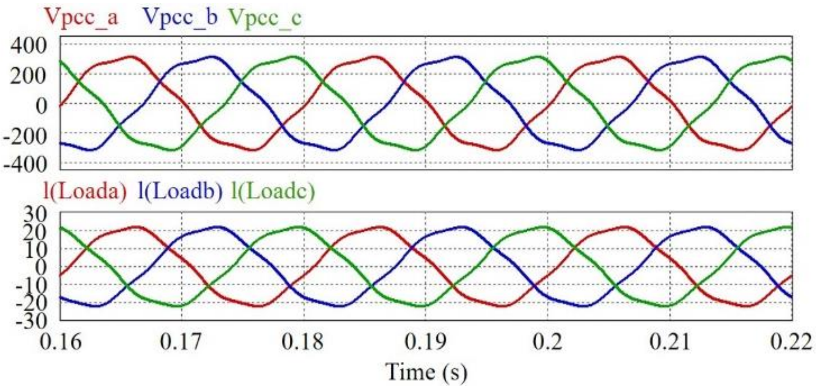

Figure 6 Without compensation: the PCC voltages (= load voltages) (top) and load currents (bottom)

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos\theta & \cos(\theta - j) & \cos(\theta + j) \\ sin\theta & \sin(\theta - j) & \sin(\theta + j) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta & 1 \\ \cos(\theta - j) & \sin(\theta - j) & 1 \\ \cos(\theta + j) & \sin(\theta + j) & 1 \end{bmatrix} \begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} \tag{4}$$

where $j = 2\pi/3$, and θ is a phase angle of the fundamental component of the PCC voltage (using a PLL circuit).

In the *dq0* reference frame, the three-phase balanced sinusoidal reference signal ($V_{REF,\ Ph\text{-}N}$) is represented by DC reference signals, which are $V_{d\text{-}ref}$, $V_{q\text{-}ref}$ and $V_{0\text{-}ref}$. In this case, $V_{d\text{-}ref} = V_{0\text{-}ref} = 0$, and $V_{q\text{-}ref}$ equals to the peak value of the nominal phase-voltage. It is easier to build a DC signal as a reference signal than to generate a three-phase symmetrical sinusoidal reference signal [18]. The output signals of the load voltage sensors are converted to v_d, v_q and v_0. Then, they are compared to the reference signals ($V_{d\text{-}ref}$, $V_{q\text{-}ref}$ and $V_{0\text{-}ref}$). The results are error signals, which will be processed by a simple Proportional Integral (PI) controller. Thus, the tracking process takes place in DC quantity.

The output signals of the PI controller are applied to the *dq0*-to-*abc* transformation. The output of the transformation is a three-phase signal ($v_{a\text{-}d}$, $v_{b\text{-}d}$, $v_{c\text{-}d}$), which represents the disturbance signal. This three-phase signal is modulated by a triangular carrier signal to build Pulse Width Modulation (PWM) for switching operation of six IGBTs. As a result, the VSI produces compensation voltages ($-V_{Disturb}$). A LC high-pass filter is used to eliminate switching frequency ripples.

The VC-VSI output voltage will be injected to the electrical network by means of three single-phase matching transformers. The winding ratio of the matching transformer is chosen according to a working voltage of the system and the VC-VSI output voltage. Finally, the three-phase load voltage equals to the three-phase reference signal ($V_{REF,\ Ph\text{-}N}$).

3. Results and discussions

To validate the concept of the proposed three-phase four-wire multi-purpose voltage compensator with the direct load voltage controller, the system has been modeled and simulated in PSIM® simulator. Then, the performance of the compensator has been evaluated.

A typical electric network under study is described in Figure 5 [7]. The main interest is at the bus 3 (PCC), because critical or sensitive loads are connected to the PCC. In this study, the PCC voltage will be disrupted. In order to obtain a high-quality load voltage, the multi-purpose voltage compensator is inserted between the PCC (bus 3) and the loads (Figure 2).

3.1. System parameters

The VC-VSI operates on a three-phase four-wire system. The PCC voltage (phase-neutral) has a three-phase balanced fundamental component of $220V_{rms}$ ($f_1 = 50$Hz) and a three-phase balanced fifth-harmonic component. The load is three single-phase RL loads connected in star configuration. Without inserting the voltage compensator, the load voltage is the same as the PCC voltage. Figure 6 shows the three-phase PCC voltage and the load current. Total Harmonic Distortion (THD_{avg}) of $V_{PCC} = V_{Load} = 6.22\%$.

At the DC side of the VC-VSI, there is a DC source of 400V. The DC split capacitor C1 = C2 = 4mF. The AC side has a high-pass filter L = 0.25mH and C = 47μF for filtering the switching ripple [10, 18]. The frequency of a triangular carrier signal = 20kHz. Winding ratio of the matching transformer = 1. Winding connection: wye/open wye.

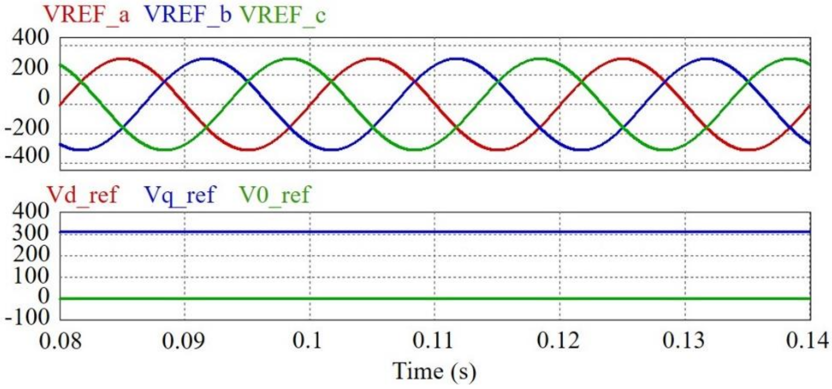

Figure 7 Reference value determination

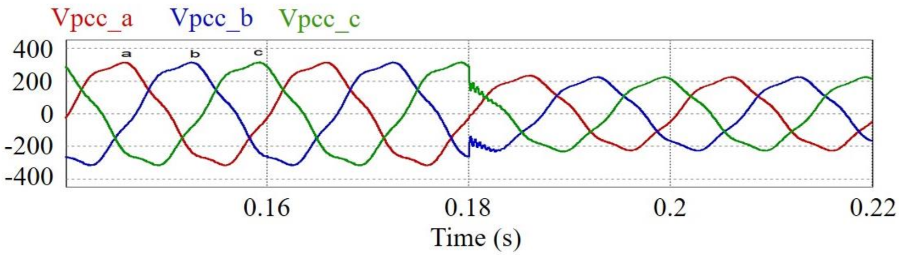

Figure 8 The PCC voltage under a balanced fault at bus 4

To determine the values of DC reference signals, simulation of the *abc*-to-*dq0* transformation based on equation (3) has been developed for transforming a three-phase balanced sinuoidal waveform at the nominal value ($220V_{rms}$) to $V_{d\text{-}ref}$, $V_{q\text{-}ref}$ and $V_{0\text{-}ref}$. Figure 7 presents the results of the transformation. Thus, $V_{d\text{-}ref} = V_{0\text{-}ref} = 0$V, and $V_{q\text{-}ref} = 310.27$V are selected as DC reference signals.

3.2. Case studies

Case studies are related to momentary voltage fluctuations, voltage distorion and voltage unbalance in accordance with the purpose of the voltage compensator. An unexpected voltage sag at the PCC occurs due to a fault at bus 4 ($Z_f = 0$). The voltage at bus 2 declines according to:

$$V_{bus-2} = \frac{Z_{24}}{Z_{24} + Z_{12}} V_{grid} \tag{5}$$

The PCC voltage (bus 3) is slightly less than $V_{bus\text{-}2}$ due to voltage drop at Z_{23}. The fault can be symmetrical (three-phase) or unsymetrical (single phase or two phases). Then, the VC-VSI could work as a harmonic filter and a voltage restorer simultaneously.

3.2.1. Three-phase balanced voltage sag

Figure 8 shows that the PCC voltage is distorted due to the fifth harmonic and decreases to $153.2V_{rms}$ due to the three-phase balanced voltage sag. Figure 9 shows that since the beginning, the VSI has injected anti fifth-harmonic voltages. At t = 0.18sec, when a balanced fault happens, the VSI also automatically generates additional voltages to offset sag voltages. Figure 10 demonstrates clearly that the load voltage is sinusoidal, balanced and stay at the nominal value. The rms values of the load voltages are as follows: V_A = 219.4V, V_B = 219.2V, V_C = 219.2V. There is still a voltage drop (ΔV_{max} = 0.36%) as well as a voltage unbalance (0.06%). However, they are considered insignificant. The other significant result is that the load harmonic voltages are decreased. THD_{avg} V_{Load} = 1.01%.

The figures confirm that the VC-VSI can reject the fifth harmonic. THD_{avg} of the load voltage is small (1.01%) compared to the PCC voltage (6.22%). Likewise, at t = 0.18sec, when a three-phase balanced fault occurs at bus 4, $V_{bus\text{-}2}$ as well as V_{PCC} decreases. The VC-VSI generates inverse sag voltages. The drop voltage is opposed by the VC-VSI output voltage so that V_{Load} stays at the nominal value.

By a direct load voltage controller, the VSI automatically produces inverse disturbance voltages without measuring and determining $V_{Disturb}$ according to Figure 3. From equations (1) and (2) about KVL, when the controller forces the load voltage equal to V_{Fund}, then the VSI instantly generates anti $V_{Disturb}$. The controller can track a three-phase balanced sinusoidal reference signal ($V_{REF,\ Ph\text{-}N}$) perfectly. There are 2 factors supporting the perfect tracking process. The first factor is a PI controller to make the error signals close to zero. Another factor is that the process is implemented in DC quantity so that it is simple and reduces the error.

The result leads to a contant and sinusoidal load voltage as well as a load current (Figure 11). Due to series connection, the PCC current and the matching transformer current are the same as the load current, which is a fundamental current (= $15.6A_{rms}$). These currents will not distort the power system. The amount of currents depends on the load variation and not on the voltage variation. Since the current is constant, the load power is also contant. When the voltage at the PCC changes, the power from PCC changes as well. The power is generated by the VSI is the difference between the power taken from the system (PCC) and the load power. Consequently, the power from the VSI will also vary to supply the power fluctuation from the PCC (Figures 12 and 13). The active and reactive power are calculated as follows [22]:

$$p = v_a i_a + v_b i_b + v_c i_c \tag{6}$$

$$q = \frac{1}{\sqrt{3}}[(v_a - v_b)i_c + (v_b - v_c)i_a + (v_c - v_a)i_b] \tag{7}$$

Moreover, Figure 9 illustrates that at t = 0.18sec, when a suddent voltage sag occurs, it looks like the response of the PI controller with triangular modulation is not quick enough.

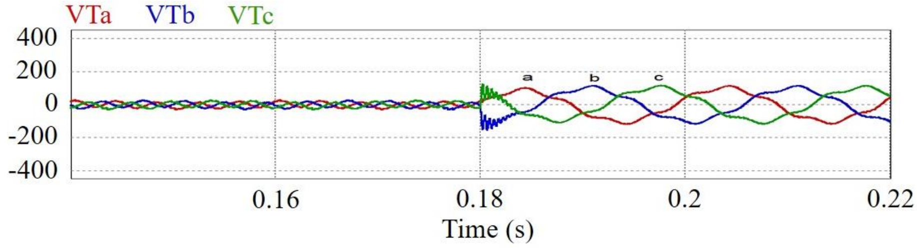

Figure 9 The compensation voltage for harmonic and sag due to a balanced fault

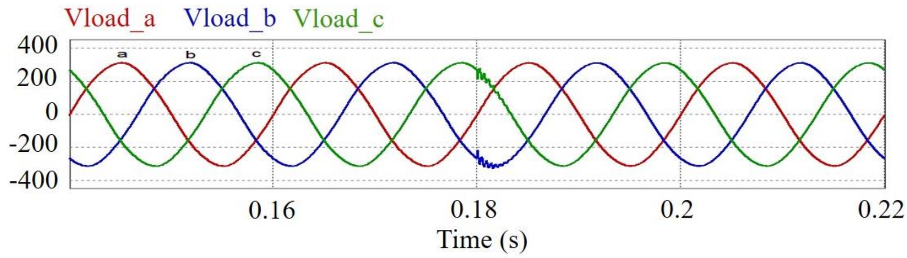

Figure 10 The load voltage after compensation for a balanced fault

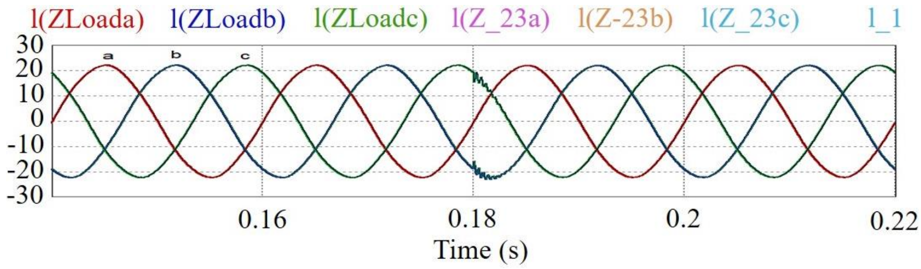

Figure 11 Load currents (= PCC currents = Transformer currents) after compensation

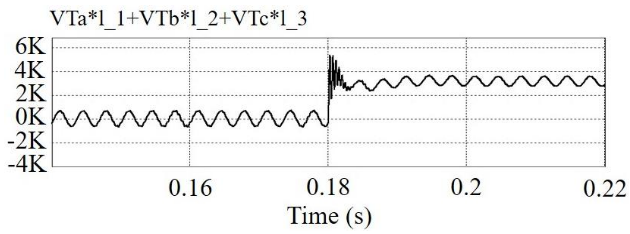

Figure 12 Active power from the VC-VSI for a balanced fault

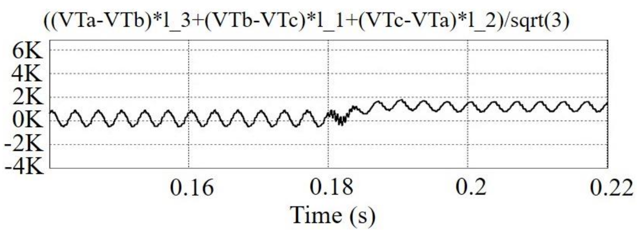

Figure 13 Reactive power from the VC-VSI for a balanced fault

Consequently, there is a notch on the load voltage waveforms. But the notch appears in a short time (0.6ms), which can be ignored. The THD of the load voltage is small (1.01%). For a fast response, a sliding mode type of controllers such as a hysteresis or a ramptime controller [20, 23] might be an option. These controllers may also improve the steady state performance.

3.2.2. Single-phase unbalanced voltage sag

Another case, the multi-purpose voltage compensator is also able to compensate for the unbalanced voltage sag (Figure 14). A single-phase voltage sag due to a single line to ground fault (SLGF) is common for a three-phase four-wire system. The fault happens at phase-B.

Figure 15 confirms that the compensation for unbalanced voltage sag is successful. The load voltage becomes balanced, sinusoidal and constant at the nominal value. The rms value of V_A = 219.5V, V_B = 219.6V, V_C = 218.9V. Figure 15 also shows that there is still a voltage drop ($\Delta V_{\max}$ = 0.5%) as well as a voltage unbalance (0.2%). But they are considered insignificant. The harmonic voltage is significantly declined (THD$_{\text{avg}}$ V_{Load} = 1.02%).

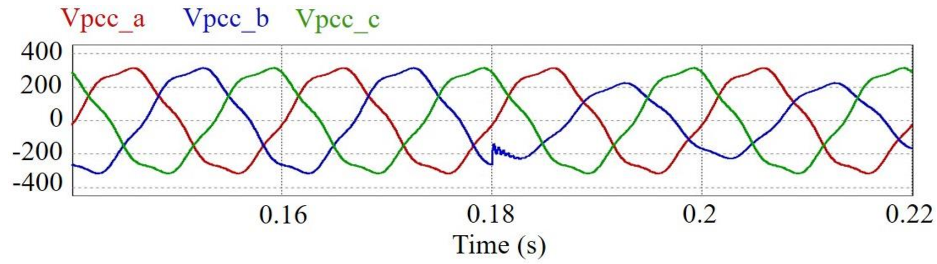

Figure 14 The PCC voltage under a phase-B fault (SLGF) at bus 4

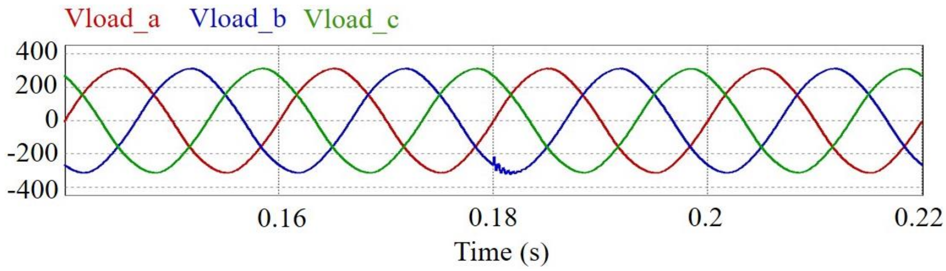

Figure 15 The load voltage after compensation for an unbalanced fault

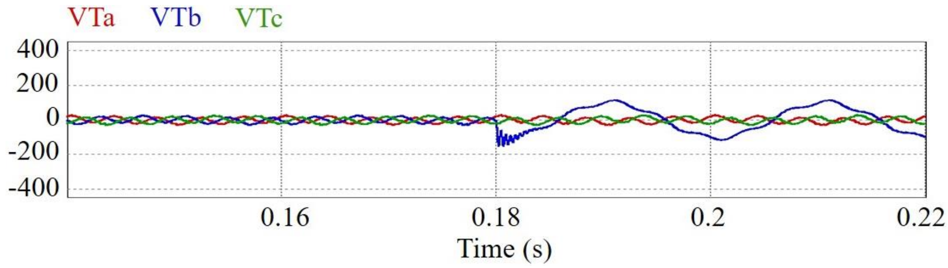

Figure 16 The compensation voltage for harmonic and voltage sag due to unbalanced fault (SLGF)

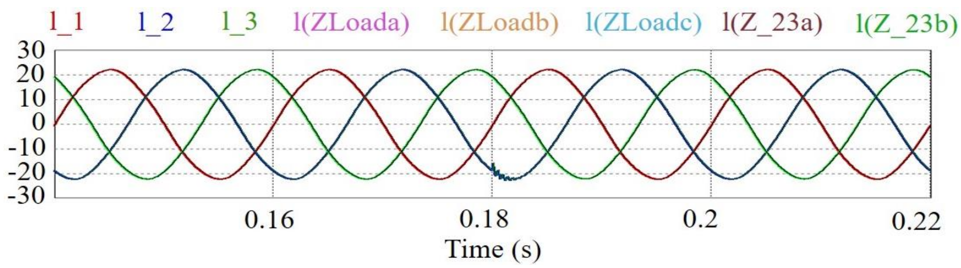

Figure 17 Load currents (= PCC currents = Transformer currents) after compensation

Like the three-phase fault, the VC-VSI is automatically able to create the inverse disturbance voltage simply by following the voltage summation rule (KVL). As can be seen from equations (1) and (2), when the controller concentrates to force the load voltage for each phase to be the same as $V_{REF,\ Ph\text{-}N}$ (= V_{Fund}), then the VC-VSI instantly creates any $V_{Disturb}$ shape, including an unbalanced voltage drop. The direct load voltage controller performs correctly for each phase without measuring dan calculating the negative- and zero-sequence components. The tracking process in DC quantity using *abc*-to-*dq0* transformation and its inverse is successful. Figure 16 shows that from t = 0.18sec, the VSI automatically creates an additional voltage to restore the sag voltage in phase B.

Similar to the three-phase case, the load currents as well as the PCC currents are constant, balanced and sinusoidal (Figure 17). The load power is also contant. When the voltage at the PCC fluctuates, the power from PCC fluctuates as well. The power from the VSI will also vary to supply the power fluctuation (Figures 18 and 19).

3.2.3. Three-phase balanced voltage swell

The third case, the multi-function voltage compensator also has capability to handle the voltage rise (swell). It commonly occurs when switching off a heavy load. In this case, a balanced voltage swell is chosen for a three-phase four-wire system.

Figure 20 demonstrates that the PCC voltage rises from the nominal value to 267V_{rms} at t = 0.18sec. Then, by directly controlling the load voltage, the VSI automatically produces the nagative voltage as well as the anti fifth harmonic voltage to reduce the voltage rise as well as to cancel the fifth harmonic voltage (Figure 21). The compensator performs successfully to handle the voltage swell without detecting dan calculating the voltage increase. The mitigation process is the same as for the three-phase balanced voltage sag. The VC-VSI instantly generates anti $V_{Disturb}$ according to KVL by tracking a three-phase balanced sinusoidal reference signal ($V_{REF,\ Ph\text{-}N}$). The tracking process takes place in DC quantity. The load voltage becomes a high-quality voltage (Figure 22). The rms value of V_A = 219.3V, V_B = 219.5V, V_C = 219.5V. The Total Harmonic Distortion of the

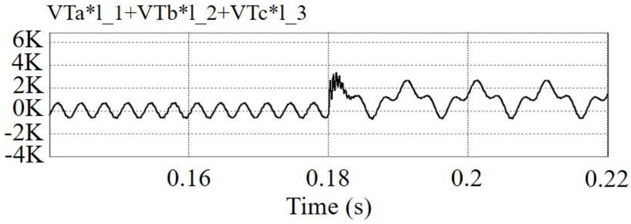

Figure 18 Active power from the VC-VSI for an unbalanced fault

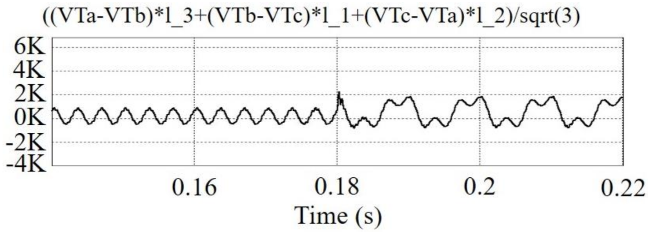

Figure 19 Reactive power from the VC-VSI for an unbalanced fault

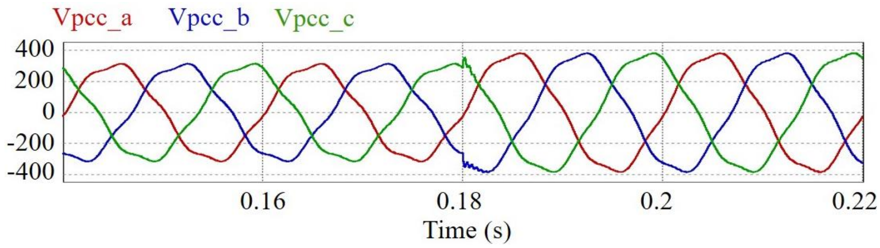

Figure 20 The PCC voltage under voltage rise

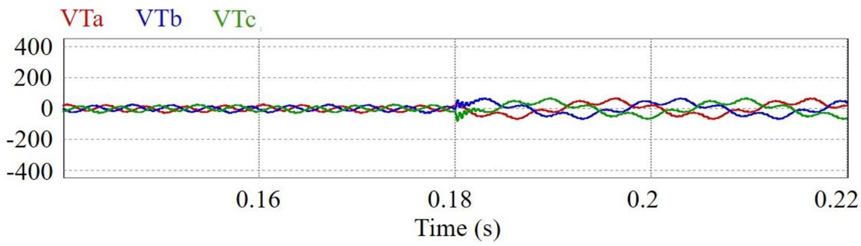

Figure 21 The compensation voltage for harmonic and voltage rise

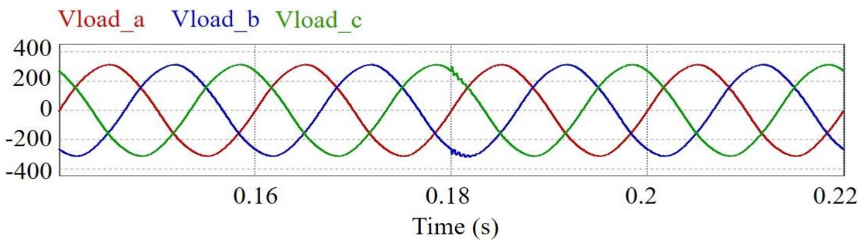

Figure 22 The load voltage after compensation for voltage rise

load voltage is reduced as well (THD_{avg} V_{Load} = 1.02%). Hence, the VC-VSI can compensate not only for voltage sag but also for voltage swell.

Similar to the case of three-phase voltage sag, the load current and the PCC current are constant, balanced and sinusoidal (Figure 23). The load power is contant as well. When the voltage at the PCC fluctuates, the power from PCC fluctuates as well. The power from the VSI will also change to supply the power fluctuation (Figures 24 and 25).

3.3. Load voltage distortion

Nowadays, non-linear loads are common in residential and commercial buildings. LED lamps, air conditions, computers need power electronic converters in their operation. Those non-linear loads produce harmonic voltages and currents to the electrical network [23]. Consequently, the source voltages will be distorted.

Due to the location of the voltage compensator, it cannot overcome load-voltage problems coming from the load side. The load voltage node is always tied to non-linear loads and distorted by the load harmonic voltage. The direct load voltage controller has no capability to reduce the harmonic voltage due to non-

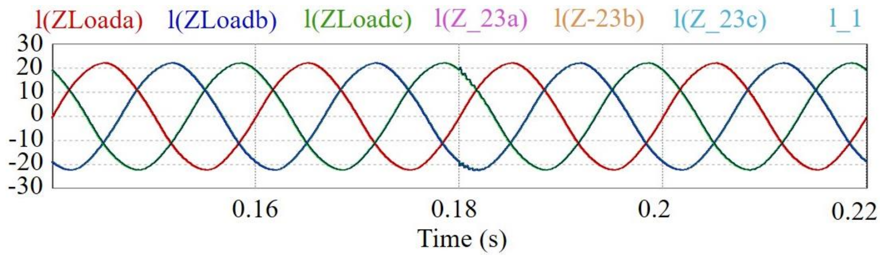

Figure 23 Load currents (= PCC currents = Transformer currents) after compensation

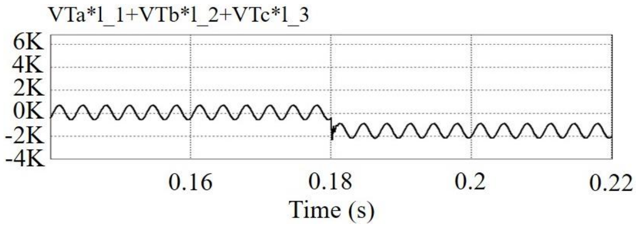

Figure 24 Active power from the VC-VSI for voltage rise

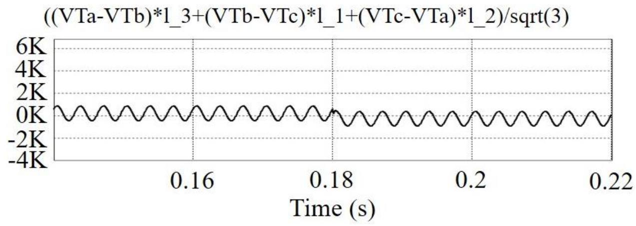

Figure 25 Reactive power from the VC-VSI for voltage rise

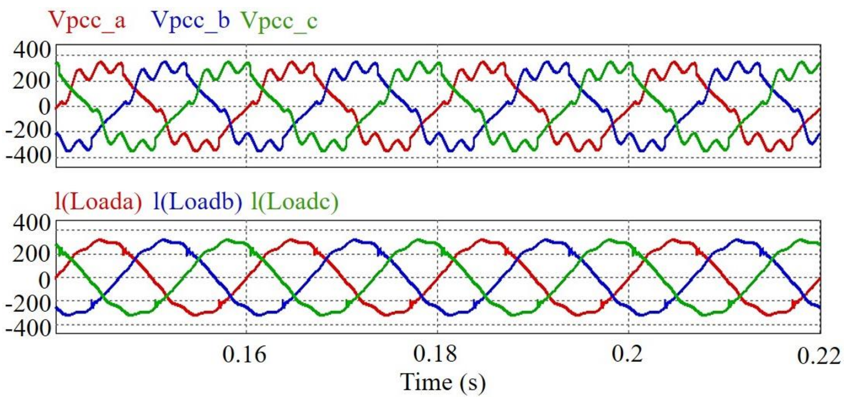

Figure 26 The PCC voltage (top) and the load voltage (bottom) due to non-linear loads

linear loads at the load side since KVL cannot be applied. Figure 26 confirms that the voltage at the load/customer side get impact from the non-linear loads. The load voltage is distorted (THD$_{avg}$ V_{load} = 4.11%). Hence, for non-linear loads connected to the load side, they must be equipped with a harmonic filter.

The PCC voltage is also distorted. Its THD$_{avg}$ is increased to 17.4%. This is because the compensator is not intended to produce a high-quality PCC voltage. Moreover, the position of voltage sensors is at the load side. So, there is no feedback operation to control the PCC voltage. As mention before, the PCC voltage quality is affected by the power system environment, not by the compensator operation. The distortion from non-linear loads increases the distortion on the PCC voltage. For directly controlling the PCC voltage to be a good quality voltage due to non-linear loads, the voltage sensors must be placed at the PCC side.

3.4. Comparison to the conventional compensator

In the conventional voltage compensator, it is necessary to detect the PCC voltages and calculate a $V_{Disturb}$ component of $V_{Source\ (PCC)}$. Thus, voltage sensors are located on the PCC. The sensor output signals are compared with $V_{REF,\ Ph\text{-}N}$ to create a reference signal ($-V_{Disturb}$) for the VC-VSI. Other voltage sensors are mounted on the output of VC-VSI for tracking the reference signal to produce compensation voltages. The expected result is that the three-phase load voltage is sinusoidal, balanced and constant at nominal value.

For comparison, it employs the same system. SLGF (phase B) at bus 4 is chosen as a disturbance case (Figure 14). The controller uses the *abc*-to-*dq0* transformation and its inverse as well. The compensation result is shown in Figure 27. The load voltage is sinusoidal, balanced and constant at the nominal value. Comparing to the compensator with a direct load voltage controller, the conventional compensator produces slightly lower load voltage quality (Table 1) with THD$_{avg}$ of 1.51%. Moreover, the dynamic response of the conventional compensator as well as

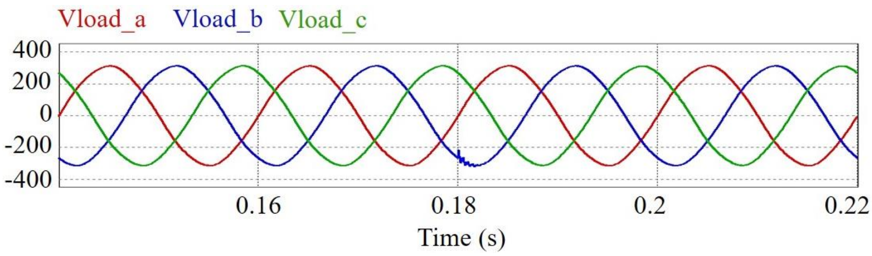

Figure 27 The load voltage after compensation for an unbalanced fault (SLGF) using the conventional compensator

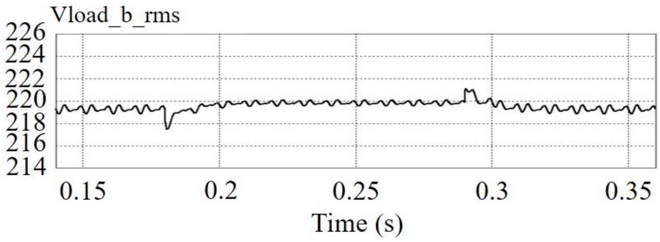

Figure 28 The dynamic response of the conventional compensator for an unbalanced fault (SLGF)

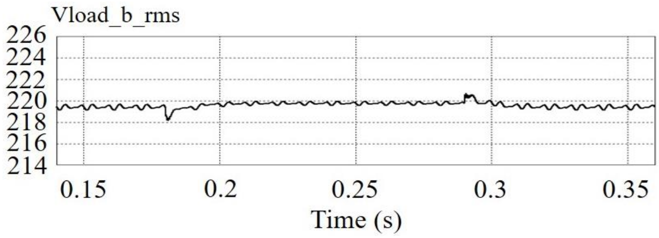

Figure 29 The dynamic response of the proposed compensator for an unbalanced fault (SLGF)

Table 1 Comparison results between the proposed compensator and the conventional compensator

Parameters	**Proposed compensator**	**Conventional compensator**
$V_{load\text{-}rms}$	V_A = 219.5V, V_B = 219.6V, V_C = 219.0V	V_A = 219.2V, V_B = 219.5V, V_C = 219.1V
V_{load} THD_{avg}	1.02%	1.51%
During SLGF V_B (t=0.18sec) V_B (t=0.29sec)	 218.2V 220.7V	 217.5V 221.2V

the proposed compensator is shown in Figures 28 and 29. The figures describe the load voltage (*rms* – phase B) when the fault occurs at t = 0.18sec, and when the system returns to a normal condition at t = 0.29sec. The dynamic response characteristics of both compensators are similar. However, the conventional compensator has a deeper voltage drop (at t = 0.18sec, V_B = 217.5V) and a higher voltage rise (at t = 0.29sec, V_B = 221.2V). For the proposed compensator, at t = 0.18sec, the load voltage drops to 218.2V, and at t = 0.29sec, the load voltage rises to 220.7V. Hence, additional sensors and control steps degrade the performance of the conventional compensator. It is obvious that the compensator with a direct load voltage controller is simpler, easier to implement and has better performance.

4. Conclusions

The VSI works as a three-phase multi-function voltage disturbance compensator for a three-phase four-wire system. For voltage compensation, the VSI is operated as a voltage-controlled VSI (VC-VSI). The VSI is connected in series between the PCC and critical loads by three single-phase matching transformers. The transformer primary windings are connected in star configuration.

The direct load voltage controller supported by a simple PI controller in *dq0* reference frame regulates the VC-VSI to automatically generate a proper output voltage ($-V_{Disturb}$) for eliminating voltage disturbances from the supply. The controller focus on directly controlling the load voltage rather than the VC-VSI output voltage. As a result, the load voltage is sinusoidal, symmetrical and constant at the normal value.

Computer simulation using PSIM simulation program verifies that the VC-VSI is successful to compensate for the harmonic voltage and the balanced/unbalanced voltage sag/swell. The performance of the VC-VSI is satisfied. Although there is still a voltage drop and a voltage unbalance, but the deviation is small and considered insignificant. Comparing to the convensional controller, the load voltage quality due to the direct load voltage controller is better. Its THD_{avg} (1.02%) is lower than THD_{avg} of the conventional compensator (1.51%).

Hence, by applying the VSI as the load voltage-controlled inverter, the sensitive/critical loads such as electronic or computer based equipments are prevented from supply voltage disturbances. In this paper, disturbance cases refer to voltage distorsion and fluctuation above specified values such as harmonics and balanced/unbalanced voltage sag/swell. As a result, the high quality of the load voltage is achieved. However, the VC-VSI has no capability to overcome voltage problems from the load itself.

An example is non-linear loads that distort the load voltage. The VC-VSI cannot eliminate this disturbance.

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