A simple three-phase three-wire

by Hanny Tumbelaka

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ICITACEE

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GREETINGS FROM THE GENERAL CHAIR

Welcome to 2014 1st International Conference on Information Technology, Computer, And Electrical Engineering (ICITACEE) held in Semarang, the capital city of Central Java! This conference provides a forum for researchers, academicians, professionals, and students from various engineering backgrounds and also from cross-disciplinary research in the development and the design of Information Technology & Computer, Power System, Circuit & Control, and Communication Systems, as well as the Interdisciplinary topics to interact and to disseminate the latest issues and research.

The ICITACEE 2014 is held in the ICT building of Diponegoro University on November, 8. Three distinguished scholars will start the session as keynote speakers: Prof. Hiroshi Ochi as a wireless expert from Kyushu Institute of Technology Japan, Dr. Trio Adiono as an IC design expert from Bandung Institute of Technology, and Mr.Adi Rahman Adiwoso as an aeronautics expert from PT Pasific Satellite Nusantara. We are very grateful for them to share their knowledge, experience, and their motivation for always doing the best. We recently received more than 140 papers, however only of 87 high quality papers were accepted and being presented in this event. All the accepted and presented papers will be then published in the IEEE Xplore (ISBN 978-1-4799-6432-1). We will select the best papers of each categories mentioned above.

Organizing such an ambitious conference has always been incredibly challenging and would have been impossible to happen without our outstanding committee supports. I would like to thanks all staffs of Department of Electrical Engineering and Department of Computer System as well as IEEE Student Branch of Diponegoro University. They have been working very hard and been always providing me with unprecedented support, advice, and kind assistance on all aspects of the conference. Special thanks goes to the IEEE Indonesia Section, Cisco, Des Net, and PSN for all support to ICITACEE 2014. I also would like to thank all of the steering commitee, technical program commitee, reviewers, authors, session organizers and chairs, and other volunteers and participants. I expect that everyone is able to enjoy some of what Semarang City has to offer! Hopefully The ICITACEE 2014 conference would become the event of our best deeds.

Wahyul Amien Syafei
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2014 1st International Conference of Information Technology,
Computer and Electrical Engineering (ICITACEE)

FOREWORD FROM HEAD OF DEPARTMENT OF ELECTRICAL ENGINEERING, UNIVERSITAS DIPONEGORO, SEMARANG-INDONESIA

It is pleasant to welcome all the participants in the International Conference on Information Technology, Computer, and Electrical Engineering (ICITACEE 2014) at Semarang. This is the second conference held together by Electrical Engineering Department and Computer System Department of Engineering Faculty Universitas Diponegoro. I would like to welcome several keynote speakers from Kyushu Institute of Technology Japan and Institut Teknologi Bandung.

As the Chief of Electrical Engineering Department Universitas Diponegoro, I would like to appreciate the vast work in this conference as collaborative effort among Electrical Engineering Department, Computer System Department Universitas Diponegoro, IEEE Student Branch of Universitas Diponegoro and IEEE Indonesia Section. I also wish that this conference to be a needed forum for engineers and scientist to communicate and sharing their findings and precious researches.

I would like to express hearty gratitude to Organizing Committee members, staffs, and students of Electrical Engineering and Computer System Department of Universitas Diponegoro for their efforts and supports. I do expect that this conference will give important contribution to development of Electrical Engineering and Computer Science locally and internationally.

Ir. Agung Warsito. D.H.E.T
Head, Department of Electrical Engineering – Faculty of Engineering
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and
Vice Chairman of FORTEI (Indonesia Electrical Engineering Forum)

FOREWORD FROM DEAN OF FACULTY OF ENGINEERING UNIVERSITAS DIPONEGORO, SEMARANG – INDONESIA

The International Conference on Information Technology, Computer, and Electrical Engineering (ICITACEE 2014) is now held in Semarang, Indonesia and being organized under the collaborative committee effort among Electrical Engineering and Computer System Department Diponegoro University and IEEE (Institute of Electrical and Electronics Engineers) Indonesia Section. This event also becomes a part of 56th Faculty of Enginering Dies Natalis and 57th Diponegoro University Dies Natalis agenda

The goals of the conference are to obtain and extend the knowledge of the recent issues, opinions, bright ideas about the development of a comprehensive green technology constructively from distinguish scholars, researchers, and academics. Furthermore, this forum is expected to bring new innovations in technology for a better future, especially in the field of information technology, computers, and electrical engineerings and also create cooperation between institutions of science at the college level, industries and government.

It is a great pleasure to welcome all the participants of this conference and also several keynote speakers from Kyushu Institute of Technology Japan, Bandung Institute of Technology and Pasific Satelite Nusantara.

I do hope that this conference to be a valuable forum for engineers and scientist to share their precious researches and this event will give significant contributions to the development of Electrical Engineering and Computer Science. It is hope that this conference will rise the awareness of scientific community members in bringing better life.

I hope that the conference will be stimulating and memorable for you. So, enjoy your time in Semarang.

Ir. Bambang Pudjianto, M.T.
Dean, Faculty of Engineering
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2014 1st International Conference on Information Technology, Computer and Electrical Engineering (ICITACEE)

CONFERENCE PROGRAM

SATURDAY, 8 NOVEMBER 2014

7:30 - 8:00	Registration			
8:00- 8:45	Opening ceremony			
	Photo session			
8:45 - 9:00	Coffee break			
9:00 - 9:50	Invited speaker 1: Prof. Hiroshi Ochi (*Kyushu Institute of Technologi, JAPAN*) *Multi-MIMO Wireless System - from Theory to Chip Design*			
9:50 - 10:40	Invited speaker 2: Prof. Dr. Trio Adiono (Institut Teknologi Bandung) *Challenges and Opportunities in Designing Internet of Things*			
10:40 - 11:30	Invited speaker 3: Dr. Adi Rahman Adiwoso (PT. Pasifik Satelit Nusantara) *Role of Satellite Telecommunication in Indonesia*			
11:30 - 12:30	LUNCH BREAK			
12:30 - 15:00	Parallel session 1			
	ROOM A	ROOM B	ROOM C	ROOM D
15:00 - 15:15	coffee break			
15:15 - 17:30	Parallel s ession 2			
	ROOM A	ROOM B	ROOM C	ROOM D
18:30 - 20:00	GALA DINNER			

SUNDAY, 9 NOVEMBER 2014

8:00 - …	*cultural program (city tours)* *(*with additional arrangements)*

PARALLEL SESSION

TIME	NO	ROOM A (HALL, 5th FLOOR) CODE	ROOM A TITLE	ROOM B (5th FLOOR) CODE	ROOM B TITLE	ROOM C (4th FLOOR) CODE	ROOM C TITLE	ROOM D (4th FLOOR) CODE	ROOM D TITLE
12.30 - 15.00	1	PS01	Design and Implementation of Solar Power as Battery Charger Using Incremental Conductance Current Control Method based on dsPIC30F4012	IP01	Visual Object Tracking using Particle Clustering	CC01	Enhancement of DRAMs Performance using Resonant Tunneling Diode Buffer	ITC01	The Development of 3D Educational Game to Maximize Childrenâ€™s Memory
	2	PS02	An Adaptive Neuro Fuzzy Inference System for Fault Detection in Transformers by Analyzing Dissolved Gases	IP02	Selective Encryption of video MPEG use RSA Algorithm	CC02	Real-time SoC Architecture and Implementation of Variable Speech PDF based Noise Cancellation System	ITC02	The Influence of Knowledge Management to Succesful Collaborative Design
	3	PS03	Optimal Power Flow based upon Genetic Algorithm deploying Optimum Mutation and Elitism	IP03	Analytical Hierarchy Process for Land Suitability Analysis	CC03	Application of Supervised Learning in Grain Dryer Technology Recirculation Type Cooperated with Wireless Sensor Network	ITC03	Knowledge and Protocol on Collaborative Design Selection
	4	PS04	Design Analysis and Optimization of Ground Grid Mesh of Extra High Voltage Substation Using an Intelligent Software	IP04	Training Support for Pouring Task in Casting Process using Stereoscopic Video See-through Display - Presentation of Molten Metal Flow Simulation Based on Captured Task Motion -	CC04	Design of Real-Time Gas Monitoring System Based-on Wireless Sensor Networks for Merapi Volcano	ITC04	Mobile-Based Learning Design with Android Development Tools
	5	PS05	Design and Simulation of Neural Network Predictive Controller Pitch-Angle Permanent Magnetic Synchrounous Generator Wind Turbine Variable Pitch System	IP05	Feature Extraction and Classification of Heart Sound based on Autoregressive Power Spectral Density	CC05	ANFIS Application for Calculating Inverse Kinematics of Programmable Universal Machine for Assembly (PUMA) Robot	ITC05	A mobile diabetes educational system for Fasting Type 2 Diabetes in Saudi Arabia
	6	PS06	Inverse Clarke Transformation based Control Method of a Three-Phase Inverter for PV-Grid Systems	IP06	Smart-Meter based on current transient signal signature and constructive backpropagation method	CC06	MRC NN Controller for Arm Robot Manipulator	ITC06	Aggressive Web Application Honeypot for Exposing Attackerâ€_s Identity
	7	PS07	Control of a Single Phase Boost Inverter with the Combination of Proportional Integrator and Hysteress Controller	IP07	AUTOMATIC DOORSTOP SAFETY SYSTEM BASED ON IMAGE PROCESSING WITH WEBCAM AND SCANNER	CC07	Development of Microcontroller-based Stereoscopic Camera Rig Positioning System	ITC07	Adjustment Levels for Intelligent Tutoring System using Modified Items Response Theory
	8	PS08	A Simple Three-phase Three-wire Voltage Disturbance Compensator	IP08	Palmprint Identification for User Verification based on Line Detection and Local Standard Deviation	CC08	Design of A Digital PI Controller for Room Temperature on Wireless Sensor and Actuator Network (WSAN) System	ITC08	Smile Recognition System based on Lip Corners Identification
	9	PS09	Analysis of Protection Failure Effect and Relay Coordination on Reliability Index	IP09	Cerebellar Model Articulation Controller (CMAC) for Sequential Images Coding	CC09	Display and Interface of wireless EMG measurements	ITC09	An Integrated Framework for Measuring Information System Success Considering the Impact of Culture in Indonesia
	10	PS10	Extreme Learning Machine Approach to Estimate Hourly Solar Radiation On Horizontal Surface (PV) in Surabaya â€“East Java	IP10	A Comparative Study on Signature Recognition	CC10	Accuracy Enhancement of Pickett Tunnelling Barrier Memristor Model	ITC10	Pre-Processing Optimization on Sound Detector Application AudiTion (Android Based Supporting Media for the Deaf)
					COFFEE BREAK				
15.15 - 17.30	11	PS11	Maximum Power Point Tracking Control for Stand-Alone Photovoltaic System using Fuzzy Sliding Mode Control Maximum Power Point Tracking Control for Stand-Alone Photovoltaic System using Fuzzy Sliding Mode Control	IP11	Study of Environmental Condition Using Wavelet Decomposition Based on Infrared Image	CC11	Data Fusion and Switching Function For UAV Quadrotor Navigation System	ITC11	EVALUATION OF DISTRIBUTION NETWORK RELIABILITY INDEX USING LOOP RESTORATION SCHEME
	12	PS12	The Influence of Meteorological Parameters under Tropical Condition on Electricity Demand Characteristic: Indonesia Case Study	IP12	Very High Throughput WLAN System for Ultra HD 4K Video Streaming	CC12	Datalogger Management Software Design for Maintenance and Utility in Remote	ITC12	Efficient Message Security Based Hyper Elliptic Curve Cryptosystem (HECC) for Mobile Instant Messenger
	13	PS13	Optimal Distribution Network Reconfiguration with Penetration of Distributed Energy Resources	IP13	Iris Recognition Analysis Using Biorthogonal Wavelets Tranform for Feature Extraction	CC13	Investigation of Electrical Properties of Nanofibre Polyaniline Synthesize as Material for Sensor	ITC13	Application of Web-Based Information System in Production Process of Batik Industry Design Division
	14	PS14	Maximum Power Point Tracking Photovoltaic Using Root Finding Modified Bisection Algorithm	TE01	Data Rate of Connections Versus Packet Delivery of Wireless Mesh Network with Hybrid Wireless Mesh Protocol and Optimized Link State Routing Protocol	CC14	Reconfigurable Floating Point Adder	ITC14	Managing and Retrieval of Cultural Heritage Multimedia Collection Using Ontology
	15	PS15	Design of LLC Resonant Converter for Street Lamp Based On Photovoltaic Power Source	TE02	Empirical Studies of Wireless Sensor Network Energy Consumption for Designing RF Energy Harvesting	CC15	HOVER POSITION CONTROL WITH FUZZY LOGIC	ITC15	Individual Decision Model for Urban Regional Land Planning

	16	PS16	Power Loss Reduction Strategy of Distribution Network with Distributed Generator Integration	TE03	Modulation Performance in Wireless Avionics Intra Communications (WAIC)	CC16	METHODOLOGY OF FUZZY LOGIC WITH MAMDANI FUZZI MODELS APPLIED TO THE MICROCONTROLLER	ITC16	Enhancing Online Expert System Consultation Service with Short Message Service Interface
	17	PS17	Double Dielectric Barrier Discharge Chamber for Ozone Generation	TE04	Implementation and Performance Analysis of Alamouti Algorithm for MIMO 2—2 Using Wireless Open-Access Research Platform (WARP)	CC17	Fall Detection System Using Accelerometer and Gyroscope Based on Smartphone	ITC17	Mobile Nutrition Recommendation System For 0-2 Year Infant
	18	PS18	Leakage Current Characteristics at Different Shed of Epoxy Resin Insulator under Rain Contaminants	TE05	Period Information Deviation onthe Segmental Sinusoidal Model	CC18	Design and Implementation of Sensor Fusion for Inertia Measurement on Flying Robot Case Study: Hexacopter	ITC18	Comparison of Distance and Dissimilarity Measures for Clustering Data with Mix Attribute Types
	19	PS19	Transformer monitoring using harmonic current based on wavelet transformation and probabilistic neural network (PNN)	TE06	A Compact Dual-band Antenna Design using Meander-line Slots for WiMAX Application in Indonesia	CC19	Triple Band Bandpass Filter With Cascade Tri Section Stepped Impedance Resonator	ITC19	Determining E-commerce Adoption Level by SMEs in Indonesia Based on Customer-Oriented Benefits
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	21			TE08	Low Cost Implementation for Synchronization in Distributed Multi Antenna Using USRP/GNU-Radio	ITC24	Visualization of Condition Irrigation Building and Canal Using Web GIS Application	ITC21	Decision Support System For Stock Trading Using Decision Tree Technical Analysis Indicators and Its Sensitivity Profitability Analysis
	22			TE09	Development of the First Indonesian S-Band Radar	ITC25	Comparison of three back-propagation architectures for interactive animal names utterance learning	ITC22	Design Web Service Academic Information System Based Multiplatform
	23					ITC26	WORK IN PROGRESS - OPEN EDUCATION METRIC (OEM): DEVELOPING WEB-BASED METRIC TO MEASURE OPEN EDUCATION SERVICES QUALITY	ITC23	Effects of VANET's Attributes on Network Performance

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Abstract **– The two-leg four-switch VC-VSI with a direct load voltage controller has been developed as a three-phase multi-functional voltage disturbance compensator for a three-phase three-wire system. By controlling only two legs (two phases) of the inverter, the third leg automatically generates the correct third voltage. The VC-VSI is connected in series between the PCC and loads by three single-phase matching transformers. The transformer primary windings are connected in delta. The VC-VSI operates to directly control the load voltage rather than its output voltage using a simple PI controller. The VC-VSI is able to produce automatically a three-phase compensation voltage so that the load voltage is sinusoidal, symmetrical and constant at a nominal value. Computer simulation verifies that the VC-VSI is able to perform well as a voltage disturbance compensator, although there is still an insignificant deviation (around 1%). The THD of the load voltage reduces to 1.4%.**

Keywords – Voltage sag/swell, Harmonic Voltage, Unbalanced Voltage, Three-phase Two-leg Inverter

I. INTRODUCTION

A high quality of an electric source is important for an electric equipment to operate properly. A good three-phase AC voltage supply should be constant, sinusoidal and symmetrical. However, a real AC voltage supply experiences disturbances such as voltage sag and swell, harmonic distortion and unsymmetrical. The quality of the AC voltage supply decreases. Consequently, the electric equipment could be broken down.

There are many ways to deal with the voltage problems. One of the solutions is to install a superior electric equipment that is reliable and tolerant to disturbance. The equipment would be expensive because it is not easy to produce it. Another possible solution is to mitigate the voltage disturbances by installing a voltage compensator at the point of common coupling (PCC). The equipment compensates for disturbances so that electric loads will receive a high quality AC voltage. The examples of a voltage compensator are a series active power-filter (SAPF) and a dynamic voltage restorer (DVR), which are made of power electronic devices

SAPF is generally used to reduce voltage harmonics from an electric source. The filter consists of power electronic devices (commonly six transistors as switches) to form a voltage source inverter (VSI). The VSI is connected in series between the distorted source and loads using a matching transformer. Then the VSI injects an equal-but-opposite voltage harmonics according to its reference harmonic voltage [1,2]. As a result, the terminal voltage of loads will receive a sinusoidal voltage waveform. Losses due to voltage harmonics will be minimized. SAPF could also compensate for voltage harmonics generated by a non-linear load. In this case, the filter is inserted between the load and PCC so that other loads connected at PCC will receive a clean voltage.

DVR is mostly used to mitigate voltage sag and swell. In voltage sag or swell, the voltage of the power system fluctuates exceeding a tolerable working voltage of equipment in a period of 0.5 cycles to a few seconds. Voltage sag/swell usually happens when a load with high power is on/off or a fault occurs/disappears on the power system. Similar to SAPF, DVR is an inverter (VSI), which is connected in series between the PCC and loads using a matching transformer [3,4,5]. DVR compensates for a voltage drop/rise (ΔV) according to voltage deviations detected at the PCC so that the load voltage will be maintained at a nominal voltage.

To improve the mitigation strategy, it is a challenge to eliminate voltage harmonic and voltage sag/swell as well as voltage unbalance with one multi-functional compensator rather than applying one compensator for one specific voltage disturbance. The simultaneous compensation is possible because voltage disturbances need a series type of a compensator. However, the problem is to create an inclusive control strategy especially to generate a single reference voltage for handling several types of voltage disturbances. Therefore, a different approach is chosen, which is directly controlling the load voltage.

Moreover, since three-phase loads such as fixed- or variable-speed induction motors are the most common equipment in industries, the application of the compensator will focus on a three-phase three-wire system (a delta system). Therefore, it is a challenge to use a four-switch VSI as the main power circuit. Reducing the number of switches may reduce the cost and simplify the controller.

Hence, this paper proposes a simple and low cost three-phase voltage disturbance compensator for protection of sensitive or critical loads from voltage harmonics and voltage sag/swell as well as voltage unbalance. The expected outcome would be a constant, sinusoidal and symmetrical load voltage so that the electric equipment will operate properly within a permissible working voltage.

II. VOLTAGE COMPENSATOR CONFIGURATION

Similar to SAPF and DVR, the proposed three-phase voltage compensator is comprised of a Voltage Source Inverter (VSI) with an energy storage element or a DC source (e.g. battery) at the DC bus and a simple LC high-pass filter at the AC side to filter out switching harmonics [4,5]. The VSI is supported by a simple controller for switching transistors.

Commonly, the VSI consists of six switches (i.e. six IGBTs with anti-parallel Diodes). However, for a three-phase three-wire configuration, the number of switches can be reduced to four switches in order to reduce the cost and to simplify the controller. As a result, the power circuit of the VSI becomes two legs of switches (phase A and B) and a split capacitor in the third leg (phase C) [6]. The two-leg four-switch VSI is shown in figure 1. By controlling the two legs, the output voltage of the third leg (phase C) will be generated instantaneously following the voltage summation rule for a three-phase system:

$$V_A + V_B + V_C = 0 \quad (1)$$

$$V_{AC} + V_{BA} + V_{CB} = 0 \quad (2)$$

The VSI is connected in series between the source and loads by three single-phase matching transformers. The AC side (output) of the VSI is connected to the primary side of matching transformers. The secondary side of the transformers is inserted into an electrical network between the PCC and loads. For three-phase three-wire system, the transformer primary-windings are connected in delta (Fig. 2).

III. COMPENSATION PROCESS

For voltage compensation, the VSI is operated as a voltage-controlled VSI (VC-VSI). A controller regulates the switches of the VC-VSI so that the VSI generates a proper output voltage for eliminating the voltage disturbances. To simplify the process, the VC-VSI directly controls the load voltage ($V_{Load,\ Ph\text{-}Ph}$) rather than its output voltage (V_{OUT}). In this case, the load voltage is sensed and directly compared to a symmetrical sinusoidal reference signal ($V_{REF,\ Ph\text{-}Ph}$).

For the two-leg VSI, two voltage sensors detect two phase-phase load voltages (V_{AC} and V_{BA}). V_{AC} and V_{BA} are compared to the same phase of the reference voltages to generate error signals. The magnitude of the reference voltage should be constant at a normal value (e.g 380V_{rms}). Its phase angle should be synchronized to the fundamental component of PCC voltage (using a phase-lock-loop – PLL circuit) so that a phase jump will not occur during compensation [3,5].

Then, the error signals are modulated by a triangular carrier signal (f = 20kHz) to generate Pulse Width Modulation (PWM) for controlling the switching operation of four IGBTs as described in figure 3. A simple PI controller is employed to make the error signal become zero. As a result, the load voltage equals to the reference voltage. A simple and direct controller for the VC-VSI can be seen in figure 3. A simple LC high-pass filter is used to eliminate high frequency ripples so that V_{Load} will be the same as V_{REF}.

Hence, by directly controlling the load voltage, the VC-VSI automatically generates an output voltage as a compensation voltage.

$$V_{PCC} - V_{Load} = V_{Compensation} \quad (3)$$

$$V_{Compensation} = V_{OUT} \quad (4)$$

$$V_{Load} = V_{REF} \quad (5)$$

The output (compensation) voltage will be injected to the electrical network to eliminate voltage disturbances by using matching transformers. The winding ratio of the matching transformer is selected according to a working voltage of the system and the VC-VSI.

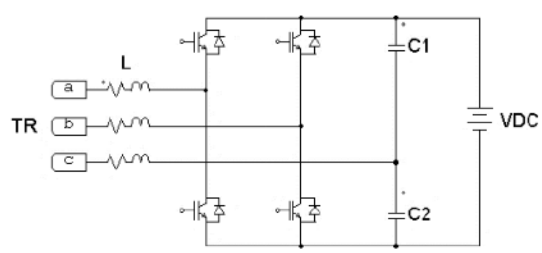

Fig. 1. Two-leg four-switch VC-VSI

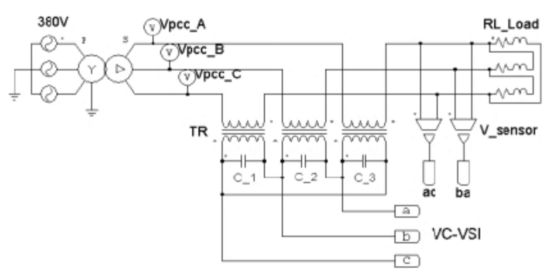

Fig. 2. Voltage Disturbance Compensator Configuration

Moreover, DC-bus capacitor voltages of the split capacitor (C1 and C2) in the third leg could be unbalance, especially at the initial condition. To minimize the capacitor voltage unbalance, a quantity (D_VC) proportional to the capacitor voltage difference (D_VC = $k\ \Delta V_C$) is added to the error signals [6]. This method is useful to improve the performance of the phase C output voltage.

The compensation process will be successful when the load voltage is the same as the reference voltage. The VC-VSI injects the compensation voltage as needed through matching transformers.

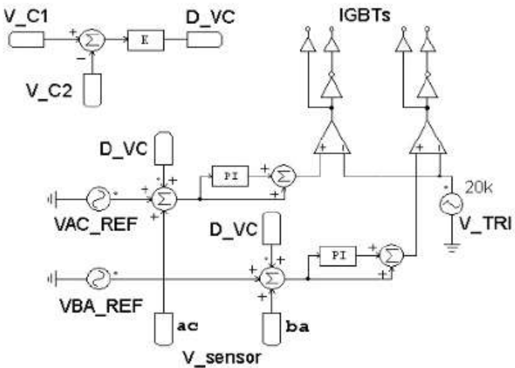

Fig. 3. A Simple and Direct Load Voltage Controller

IV. Simulation and Discussion

A. Simulation Parameter

To verify the concept of the three-phase three-wire voltage disturbance compensator, the proposed circuits (Fig. 1 to Fig. 3) have been built and simulated using PSIM® simulator. Then, the performance of the circuits will be evaluated.

The compensator is working on a three-phase three-wire system. The source voltage (phase-phase) has a fundamental component of $380V_{rms}$ (f_1 = 50Hz) and a fifth harmonic. The load is a three-phase RL load and connected in delta. Without compensation and additional voltage disturbances, the three-phase load voltage, which is the same as the voltage at the PCC, and the three-phase load current can be seen in figure 4. Total Harmonic Distortion (THD) of V_{PCC} = 6.2%.

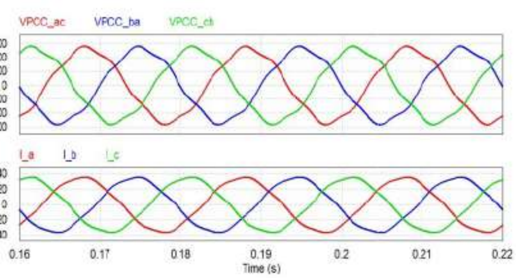

Fig. 4. The three-phase PCC voltage (= load voltage) (top) and load current (bottom) without compensation

At the DC side of the VC-VSI, there is a DC source of 575V. The split capacitor C1 = C2 = 10mF. The AC side has a high-pass filter L = 0.14mH and C = 100µF. Constants of the PI controller, K_P = 10, T_i = 0.45. The frequency of a triangular carrier signal = 20kHz. Winding ratio of the matching transformer = 1. Winding connection: delta/open-wye

B. Simulation Results

When there is no additional voltage disturbance, the voltage compensator is working as a harmonic filter to eliminate the harmonic voltage at the load from the source. As a result, figure 5 shows the clean load voltage and current. The three-phase load voltage is sinusoidal, symmetrical and constant around $377V_{rms}$ identical to the reference voltage. THD of V_{Load} decreases significantly to 1.3%. The load voltage is also in-phase with the PCC voltage. Figure 6 shows the compensation voltage at the secondary side of the matching transformers generated by the VC-VSI, which is the same as the harmonic voltage produced by the source.

Thus, by controlling only two legs of the inverter, the third leg automatically produces the proper third voltage (phase C). Moreover, by directly controlling the load voltage, automatically the VC-VSI is able to generate a three-phase anti-harmonic voltage and to eliminate the distortion at the load through the matching transformers.

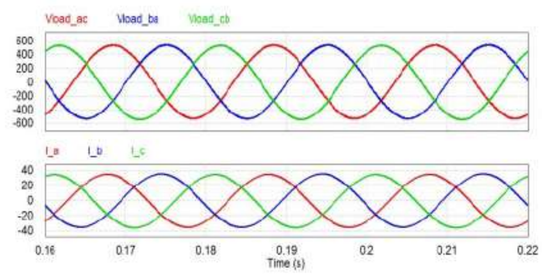

Fig. 5. The load voltage (top) and the load current (bottom) after harmonic compensation

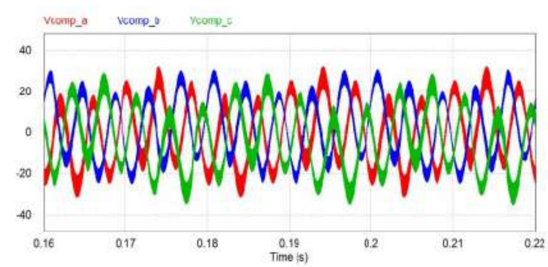

Fig. 6. Compensation for harmonic voltage

Another case, when there is a sudden voltage drop at the PCC, the voltage compensator should be able to operate as both a harmonic filter and a voltage restorer. The voltage drop could be balanced or unbalanced. The unbalanced voltage drop could be single phase or two phases.

The three-phase balanced voltage drop can be seen in figure 7. In this case, the three-phase PCC voltage decreases to $278 V_{rms}$. Similar to the previous case, by controlling the load voltage to be sinusoidal, symmetrical and constant at a normal value, the VC-VSI is able to produce the compensation voltage (Fig. 8) so that the load voltage would stay at a normal value and balance. The rms value of the load voltage are as follows: V_{AC} = 370V, V_{BA} = 379V, V_{CB} = 368V.

The performance of the load voltage can be improved by balancing the split-capacitor voltage on the third leg of the VSI. By adjusting the value of k = - 0.2, the rms value of the load voltage becomes as follows: V_{AC} = 375V, V_{BA} = 379V, V_{CB} = 376V. There is still a voltage drop (ΔV_{max} 1.3%) and a voltage unbalance (1.05%). But, the deviation is small and considered insignificant. The harmonic voltage is also eliminated (THD V_{Load} = 1.4%). The value of k = - 0.2 will be applied to all cases of voltage disturbances.

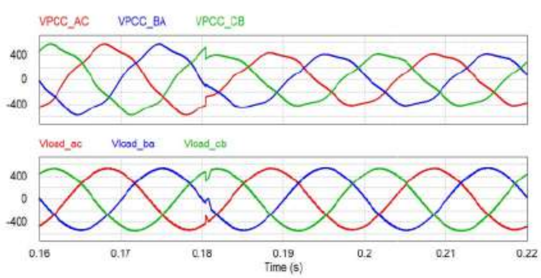

Fig. 7. The PCC voltage (top) and the load voltage (bottom) after compensation for a balanced fault

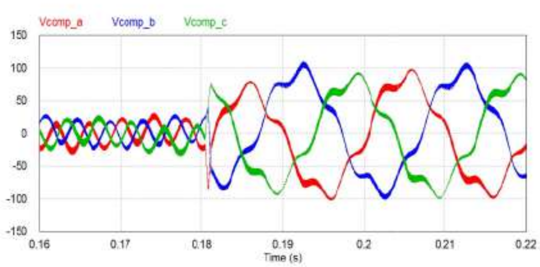

Fig. 8. Compensation for harmonic and voltage drop due to a balanced fault

From figure 7, it can be seen at t = 0.18ms, when a fault occurs, there is a notch on the load voltage waveforms. It seems that the response of a PI controller with triangular modulation is not quick enough for the sudden voltage drop so that the compensation is not successful. However, the process takes only 0.6ms, which is considered insignificant. For the fast response, a sliding mode type of controllers such as a hysteresis or a ramptime controller [5,7] might be an option. The sliding mode controller may also be able to enhance the steady state performance of a direct load voltage control system.

To prove the ability of the voltage disturbance compensator to handle the unbalanced voltage drop is described in figure 9 and 10. In this case, the two-phase unbalanced voltage drop due to a phase-to-phase fault is selected for a three-phase three-wire system.

Figure 9 shows that, after compensation, the load voltage becomes sinusoidal, symmetrical and constant. V_{AC} = 375V, V_{BA} = 378V, V_{CB} = 376V. The performance of the controller is the same as the previous case. There is still a voltage drop (ΔV_{max} 1.3%) and a voltage unbalance (0.8%). But, the deviation is small and considered insignificant. The harmonic voltage is also eliminated (THD V_{Load} = 1.4%). The VC-VSI generates the compensation voltage (Fig. 10) to maintain the load voltage at a normal value and to eliminate the harmonics. Compared to figure 8, it is proved that the VC-VSI is automatically able to generate a different compensation voltage for a different disturbance voltage as long as its operation satisfies (1) to (5).

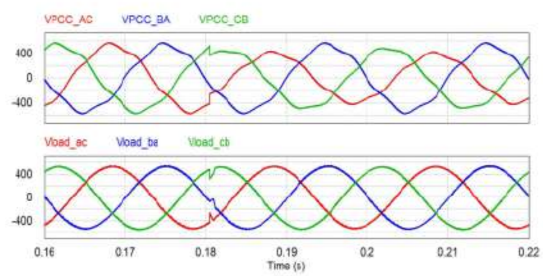

Fig. 9. The PCC voltage (top) and the load voltage (bottom) after compensation for an unbalanced (phase-to-phase) fault

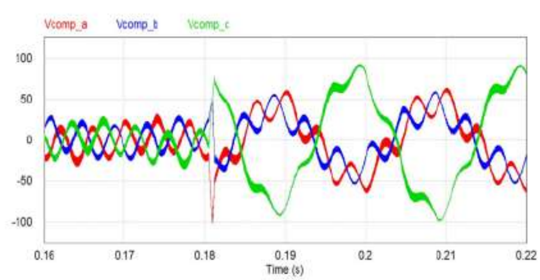

Fig. 10. Compensation for harmonic and voltage drop due to an unbalanced (phase-to-phase) fault.

The voltage compensator is also able to compensate for the voltage rise, although this phenomenon is less common than the voltage sag. In this case, a balanced voltage rise is selected for a three-phase three-wire system.

Figure 11 shows that the three-phase PCC voltage increases from a normal voltage at t = 0.18ms to become 443V_{rms}. Then, automatically the VC-VSI generates the compensation voltage (Fig. 12) to subtract the voltage rise. The load voltage is kept at a normal value. The controller performs well to handle the voltage rise. In this case, its transient response is better than the response for handling the voltage sag. The load voltage becomes sinusoidal, symmetrical and constant. V_{AC} = 377V_{rms}, V_{BA} = 376V_{rms}, V_{CB} = 378V_{rms}. The harmonic voltage is eliminated as well (THD V_{Load} = 1.4%).

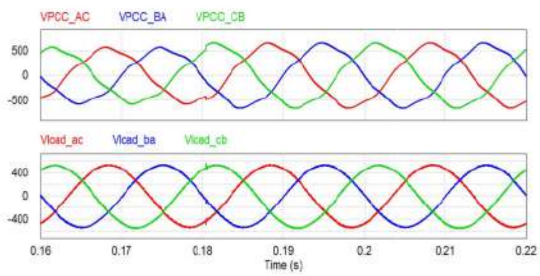

Fig. 11. The PCC voltage (top) and the load voltage (bottom) after compensation for a voltage rise

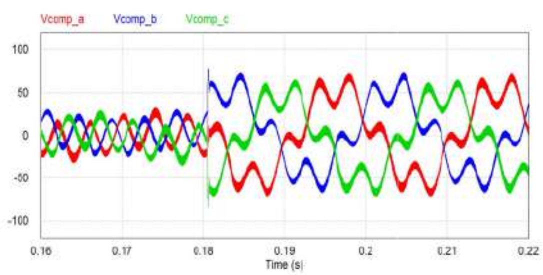

Fig. 12. Compensation for harmonic and voltage rise

V. CONCLUSION

The two-leg four-switch VSI has been proven to be used as a three-phase multi-functional voltage disturbance compensator for a three-phase three-wire system. For voltage compensation, the VSI is operated as a voltage-controlled VSI (VC-VSI). A controller regulates the VC-VSI to generate a proper output voltage for eliminating the voltage disturbances. The VC-VSI is connected in series between the PCC and loads by three single-phase matching transformers. The transformer primary windings are connected in delta.

By controlling only two legs of the inverter, the third leg automatically generates the correct third voltage (phase C) so that the VC-VSI produces a complete three-phase compensation voltage. Moreover, by directly controlling the load voltage rather than its output voltage, the VC-VSI is automatically able to generate the compensation voltage. As a result, the load voltage is sinusoidal, symmetrical and constant at a normal value.

Computer simulation verifies that the VC-VSI is able to compensate harmonic voltage and balanced/unbalanced voltage sag/swell. The performance of the VC-VSI supported by a simple PI controller is satisfied. Although there is still a voltage drop and a voltage unbalance, but the deviation is small (around 1%) and considered insignificant. The THD of the load voltage reduces to 1.4%.

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