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Research Article

Fault Strategy Analysis for Three-phase Cascaded Multi-level Inverter

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Abstract: This study includes a multilevel cascaded inverter along with a control strategy. This proposed control scheme directs the inverter to support the grid under three - phase balanced voltage sags and during one or two - phase faults. Control of voltage between grid and Distributed Generation (DG) system is a challenging subject. Integrating DG with the grid is the fundamental element of this study which depends on grid codes prescribed by the transmission system operators. These electrical dispatching standards endow smartness and flexibility of DGs. The proposed system is designed using MATLAB/Simulink tool. Simulated results show the feasibility of the proposed control scheme.

Keywords: Clarke transformation, inverter, symmetrical components, voltage sag, voltage support

INTRODUCTION

Production of power by means of renewable energy sources is gaining more popularity in the deregulated electric system. Out of the various renewable sources, wind and photovoltaic applications are more preferred in the recent years. These sources when connected to the grid, work as Distributed Generation (DG) systems. The theories about the energy systems and microgrids are changing because of these DGs as they have advantages in excess to the conventional systems. To mention a few, locations of these DGs are close to the load centre which largely reduces the power losses. Such services help in better utilization of the resources and the transmission system.

The interface between DG and the transmission system is the inverter. Fundamentally the grid can exist in two conditions; one is normal grid condition during which all the generated active power is fed to grid by means of the inverter (Serban and Serban, 2010). The normal condition prevails until an abnormality like voltage sag (dip) occurs in the transmission network. Such a situation refers to grid fault condition, at which a control is mandatory to override the fault and reduce the effects of the fault from affecting the system. The entire behaviour of the system is based on the grid codes formulated by the transmission system operators (Guo *et al*., 2014). As the use of renewable energy sources are growing, the existing codes are to be revised.

Voltage sags are of various types hence a control mechanism is required to support the grid under fault. This study features a control strategy which facilitates flexible voltage support for grid at the event of voltage sag. The strategy proposed here has two tasks to perform which includes voltage raising strategy and voltage equalising strategy during balanced three-phase voltage sag and one or two phase faults (Chattopadhyay *et al*., 2011), respectively. It is also designed in such a way that DG should not be disconnected at faulty condition because disconnection of DG would not be a feasible solution in this competitive power market.

From the literature review it is evident that the existing control methods provide optimum solution only for specific fault condition (Rodriguez *et al*., 2007). However this study proposes a stretchy voltage support in mitigating a wide range of voltage sags. The objective of this study directs the inverter to support the grid under three phase balanced voltage. The proposed system is designed using MATLAB/Simulink tool. Simulated results show the feasibility of the proposed control scheme.

FUNCTIONAL ELEMENTS

The functional elements are the building blocks of any complete system. Here Fig. 1 shows the typical configuration of a grid-connected DG system with its functional elements such as PV source with its DC link, inverter which is dictated by a controller and LCL filter in order to filter out the harmonics. Finally the system is connected to the grid at the point of common coupling.

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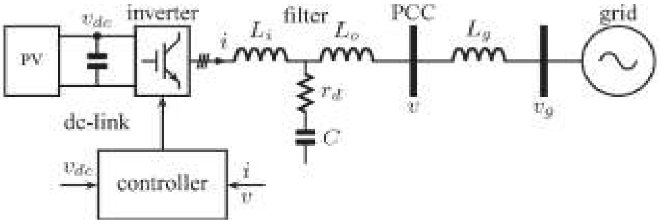

Fig. 1: Grid connected DG inverter system

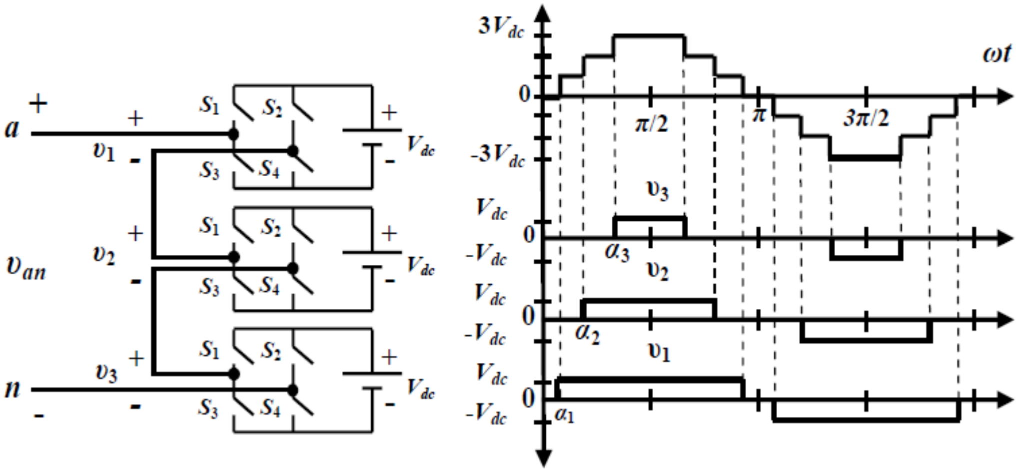

Fig. 2: Seven-level cascaded inverter with its output waveform

PV source: A photovoltaic system converts light energy into electrical energy where the incident photons create electron or hole pairs for the conduction of electricity. The basic structure of a photovoltaic system includes photovoltaic cells. Many cells constitute to form large photovoltaic modules and again many modules combine to form photovoltaic arrays. Hence the term array used means any photovoltaic device composed of several basic cells.

The proposed photovoltaic array presents a nonlinear I-V characteristic with several parameters that need to be adjusted from experimental data of practical devices. We generally know that the PV device consists of two resistances namely series resistance R_s and parallel resistance R_p. The practical device always represents hybrid behaviour by serving as both the current source and voltage source depending upon the operating point. Thus we obtain to a conclusion by analysing I-V characteristics of the PV cells that the operation of a PV device not only depend on the internal characteristic but also with external influences such as irradiation and temperature which is expressed in the Eq. (1):

$$I_{pv} = \left(I_{pv,n} + k_1\Delta_T\right)\frac{G}{G_n} \qquad (1)$$

where, G and G_n are radiation of surface and nominal irradiation, respectively (Villalva *et al*., 2009).

The proposed system is designed using MATLAB/SIMULINK using SimPowerSystems block set. Here an additional data sheet comprising of varying radiation and temperature is provided for the simulation of the system. Thus the proposed system works in such a way that the terminal of the source connected to the input of the converters and controllers. The simulation design of the PV system is shown in simulation. The simulated output shows the outputs of the PV system designed.

Multilevel inverter: The output terminal point of the PV source is connected to the grid via inverter. The three-phase six-pulse inverters used conventionally pose various difficulties such as difficulty in extending power transfer capability, requirement of step-up transformers, effects of harmonics, etc (Hochgraf *et al*., 1994). In order to overcome the above limitations we prefer the usage of multilevel inverters. The advantages of multilevel inverters include elimination of distribution transformer which greatly reduces the system cost as we go for the higher levels. The inherent quality of MLIs is its multi-step waveform which allows the operation of it without PWM thus reducing the switching losses (Fig. 2).

The proposed scheme consists of cascaded multilevel inverter over the other types of MLIs as it requires low number of components per level and no requirement of clamping components also simple voltage balancing modulation is enough.

Here we employ three-phase cascaded seven-level inverter which involves a technique called carrier based

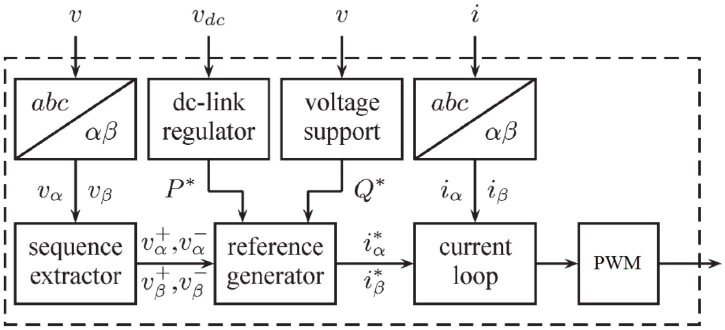

Fig. 3: Control unit for inverter under fault

pulse width modulation, in order to generate the pulses for the switching device. This carrier based PWM is used instead of SVM (Space Vector Modulation) because of its complexity. The output thus we derive is so sufficient to directly synchronize with the grid without the usage of transformers (KlempKa, 2008). The main task of this inverter is to compensate the missing voltage during sag, with the help of proposed control technique involved in carrier PWM. It is so apparent from the simulated results.

Fault description: Voltage sag is a frequent abnormality that occurs in the grid which is defined as reduction in rms voltage for a short duration in one or various phases. They mainly manifest during short circuits, overload or starting of induction motors. Voltage sags are described by positive, negative and zero symmetric sequences or by magnitude, frequency and angle of each phase. This study completely deals with the former and its associated equations which are as follows:

$$v_a = v_a^+ + v_a^- + v_a^0 \tag{2}$$

$$v_b = v_b^+ + v_b^- + v_b^0 \tag{3}$$

$$v_c = v_c^+ + v_c^- + v_c^0 \tag{4}$$

In general the natural rotating frame is used to state the voltage sag. As in this study, characterization of the voltage sag is expressed in terms of Stationary Reference Frame (SRF) by means of Clarke transformation:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{5}$$

Using the above Eq. (2)-(4) can be expressed as:

$$v_\alpha = v_\alpha^+ + v_\alpha^- \tag{6}$$

$$v_\beta = v_\beta^+ + v_\beta^- \tag{7}$$

where,

v_α^+ and v_β^+ = The positive-sequence voltages
v_α^- and v_β^- = The negative ones in the SRF

Positive and negative voltage sequences as functions of time can be represented as:

$$v_\alpha^+ = V^+ \cos(\omega t + \varphi^+) \tag{8}$$

$$v_\beta^+ = V^+ \sin(\omega t + \varphi^+) \tag{9}$$

$$v_\alpha^- = V^- \cos(\omega t - \varphi^-) \tag{10}$$

$$v_\beta^- = -V^- \sin(\omega t - \varphi^-) \tag{11}$$

where,

V^+ and V^- = The amplitudes
φ^+ and φ^- = The initial phase angles of the positive and negative sequences, respectively
ω = The grid frequency

Operation of controller: As when the faults are introduced in the grid discussed above, it is a task of the controller present in the inverter system to rectify the fault by injecting the current at PCC. In order to inject the current, the status of the grid under fault must be known. The constituents of the grid connected system such as measured phase voltage v at PCC, current i flowing through inductor L_i and the dc-link voltage V_{dc} are the inputs to the control unit. The block diagram shown in Fig. 3, gives the control system for the MLI during grid fault.

The voltage v and current i are transformed into a stationary reference (SRF) values, the obtained voltages V_α and V_β are decomposed into symmetrical components which characterizes the grid voltage. The dc-link voltage V_{dc} helps to keep the power balanced with respect to active power reference P^*. From the rms values of each phase the presence of the sag can be detected. In the event of sag, the voltage support control is activated. We obtain the reactive power reference Q^* from the measured phase voltage. With all the parameters generated above, we build the reference currents i_α^* and i_β^* which are compared with the measured currents (Guerrero *et al*., 2007). From the error value the duty cycle is generated which is the main input for driving the inverter which flexibly supports the grid according to the grid codes specified. The GCR denotes the Grid Code Requirements which recommend that power generation supplying the grid should not be disconnected under any fault condition.

METHODOLOGY

The inverter aids to infuse the entire active power extracted from the source, under balanced grid conditions. During such a case, the reference currents for active power (Camacho *et al*., 2013) are expressed as:

$$i_{\alpha(p)}^* = \frac{2}{3} P^* \frac{v_\alpha}{(v_\alpha)^2 + (v_\beta)^2} \tag{12}$$

$$i_{\beta(p)}^* = \frac{2}{3} P^* \frac{v_\beta}{(v_\alpha)^2 + (v_\beta)^2} \tag{13}$$

Likewise, equations representing reference currents for reactive power are expressed as follows:

$$i_{\alpha(q)}^* = \frac{2}{3} Q^* \frac{v_\beta}{(v_\alpha)^2 + (v_\beta)^2} \tag{14}$$

$$i_{\beta(q)}^* = \frac{2}{3} Q^* \frac{-v_\alpha}{(v_\alpha)^2 + (v_\beta)^2} \tag{15}$$

The active power reference and reactive power reference are P^* and Q^*, respectively.

During the event of unbalanced grid conditions, the symmetrical components come into picture. The reactive currents developed are:

$$i_{\alpha(q)}^* = \frac{2}{3} Q^* \frac{v_\beta^+ + v_\beta^-}{(v_\alpha^+ + v_\alpha^-)^2 + (v_\beta^+ + v_\beta^-)^2} \tag{16}$$

$$i_{\beta(q)}^* = \frac{2}{3} Q^* \frac{-v_\alpha^+ - v_\alpha^-}{(v_\alpha^+ + v_\alpha^-)^2 + (v_\beta^+ + v_\beta^-)^2} \tag{17}$$

Using (7)-(10) into the denominator of (16) and (17):

$$\begin{aligned} &(v_\alpha^+ + v_\alpha^-)^2 + (v_\beta^+ + v_\beta^-)^2 \\ &= (v_\alpha^+)^2 + (v_\alpha^-)^2 + 2v_\alpha^+ v_\alpha^- + (v_\beta^+)^2 + (v_\beta^-)^2 + 2v_\beta^+ v_\beta^- \\ &= (V^-)^2 + (V^-)^2 + 2V^+V^- \cos(2\omega t + \varphi^+ - \varphi^-) \end{aligned} \tag{18}$$

It can be noted from the above equations that oscillatory terms are present whose frequency is twice the grid frequency. This leads to harmonic distortion in reference currents which are undesirable. The crossed terms $2v_\alpha^+ v_\alpha^-$ and $2v_\beta^+ v_\beta^-$ are responsible for such cases. Hence the modified equations are:

$$i_{\alpha(q)}^* = \frac{2}{3} Q^* \frac{v_\beta^+ + v_\beta^-}{(v_\alpha^+)^2 + (v_\beta^+)^2 + (v_\alpha^-)^2 + (v_\beta^-)^2} \tag{19}$$

$$i_{\beta(q)}^* = \frac{2}{3} Q^* \frac{-v_\alpha^+ - v_\alpha^-}{(v_\alpha^+)^2 + (v_\beta^+)^2 + (v_\alpha^-)^2 + (v_\beta^-)^2} \tag{20}$$

Proposed control strategy: As already discussed in the introduction, whenever a balanced three-phase voltage sag occurs, voltage in all three phases must raise to compensate the missing voltage and whenever sag occurs in one or two phases, voltage in that particular phase or two must raise in order to equalize the three-phase voltage (Suresh and Prasad, 2012). The proposed strategy is so designed that both the above mentioned conditions are satisfied also the main concern is that the system must not get disconnected hence a balance between the two cases is also provided. This is achieved by taking into account the positive- and negative-sequence voltages as it provides different support mechanism by slightly modifying the conventional control represented in (19) and (20). The modification is achieved by introducing control parameters into (19) and (20). The balance between the positive and negative components is obtained from the following reactive current references (Camacho *et al*., 2013) which are as follows:

$$i_{\alpha(q)}^* = \frac{2}{3} Q^* \frac{k^+ v_\beta^+ + k^- v_\beta^-}{k^+\left[(v_\alpha^+)^2 + (v_\beta^+)^2\right] + k^-\left[(v_\alpha^-)^2 + (v_\beta^-)^2\right]} \tag{21}$$

$$i_{\beta(q)}^* = \frac{2}{3} Q^* \frac{-k^+ v_\alpha^+ - k^- v_\alpha^-}{k^+\left[(v_\alpha^+)^2 + (v_\beta^+)^2\right] + k^-\left[(v_\alpha^-)^2 + (v_\beta^-)^2\right]} \tag{22}$$

where, $k^+$and k^- are the control parameters to balance the voltages of positive- and negative-sequence. In order to normalize the parameters the subsequent relation is used:

$$k^- = 1 - k^+ \mid k^+ \in [0,1]$$

The proposed control scheme is expressed in (21) and (22) which are the reference for voltage maintenance that helps to either raise or equalize voltages. It can be noted that by setting different values for the control parameter k^+ different results are obtained. The conventional strategy varies from that of the proposed scheme by the stiffness of the former for different voltage sag characteristics. To obtain the desired control facility, proper tuning of one single control parameter $k^+$the voltage at the inverter side can be raised ($k^+ \to 1$), equalized ($k^+ \to 0$), or a flexible combination of both ($0 < k^+ < 1$), say ($k^+ = k^- = 0.5$. The last tuning is very essential to avoid disconnection due to over- or undervoltage as it is a blend of raising and equalizing strategy.

The active reference currents are generated by taking into account the positive-sequence voltages which are:

$$i^*_{\alpha(p)} = \frac{2}{3}P^*\frac{v^+_\alpha}{(v^+_\alpha)^2+(v^+_\beta)^2} \qquad (23)$$

$$i^*_{\beta(p)} = \frac{2}{3}P^*\frac{v^+_\beta}{(v^+_\alpha)^2+(v^+_\beta)^2} \qquad (24)$$

The active currents do not show obvious effects on voltage support. But according to specified grid codes it can be set to zero or its ratio with reactive currents can be used. Thus the total reference currents are sum of active and reactive powers which are expressed below:

$$i^*_\alpha = i^*_{\alpha(p)} + i^*_{\alpha(q)} \qquad (25)$$

$$i^*_\beta = i^*_{\beta(p)} + i^*_{\beta(q)} \qquad (26)$$

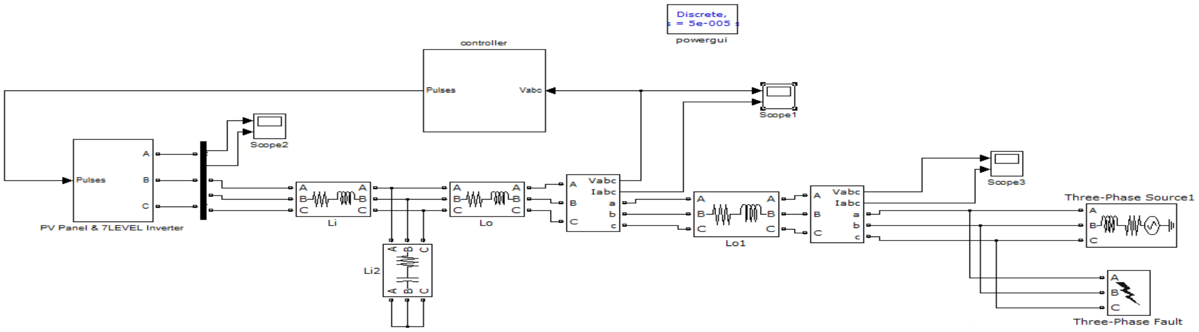

Fig. 4: Simulation model of the entire system

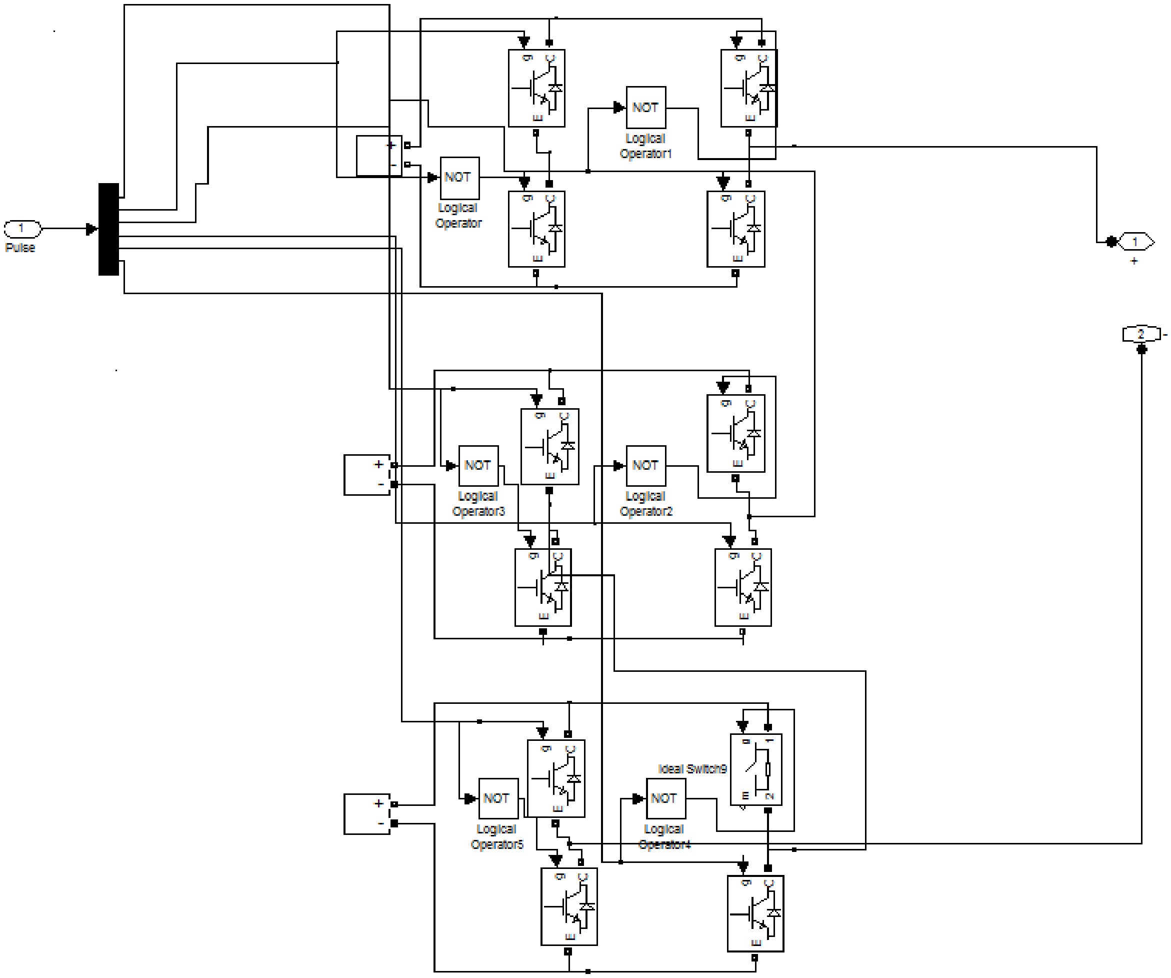

Fig. 5: Single-phase cascaded seven-level inverter

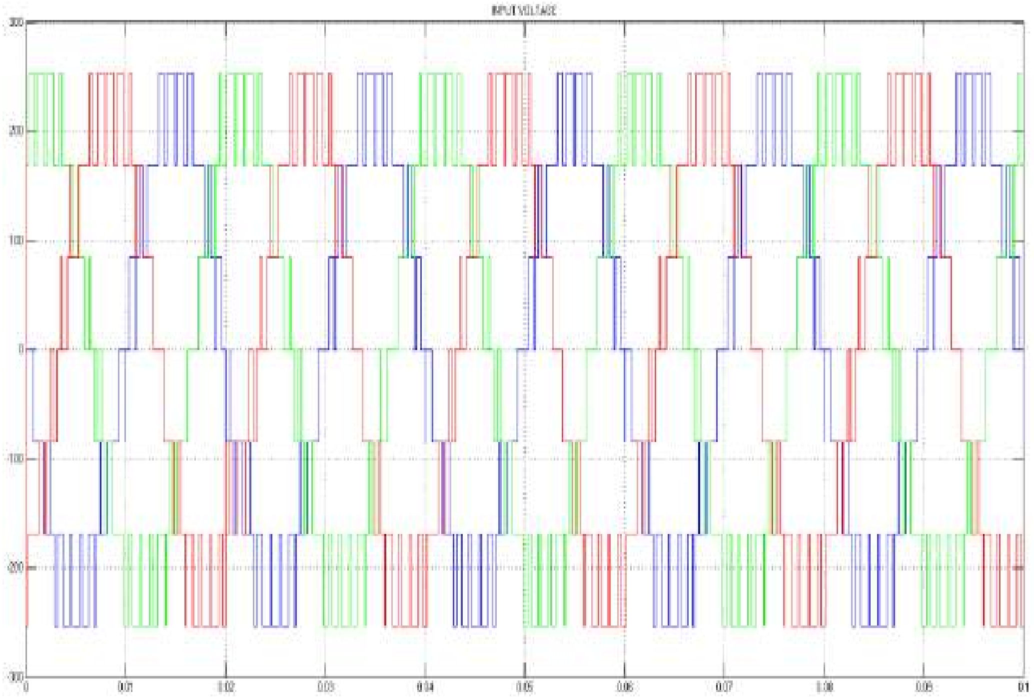

Fig. 6: Output voltage from inverter

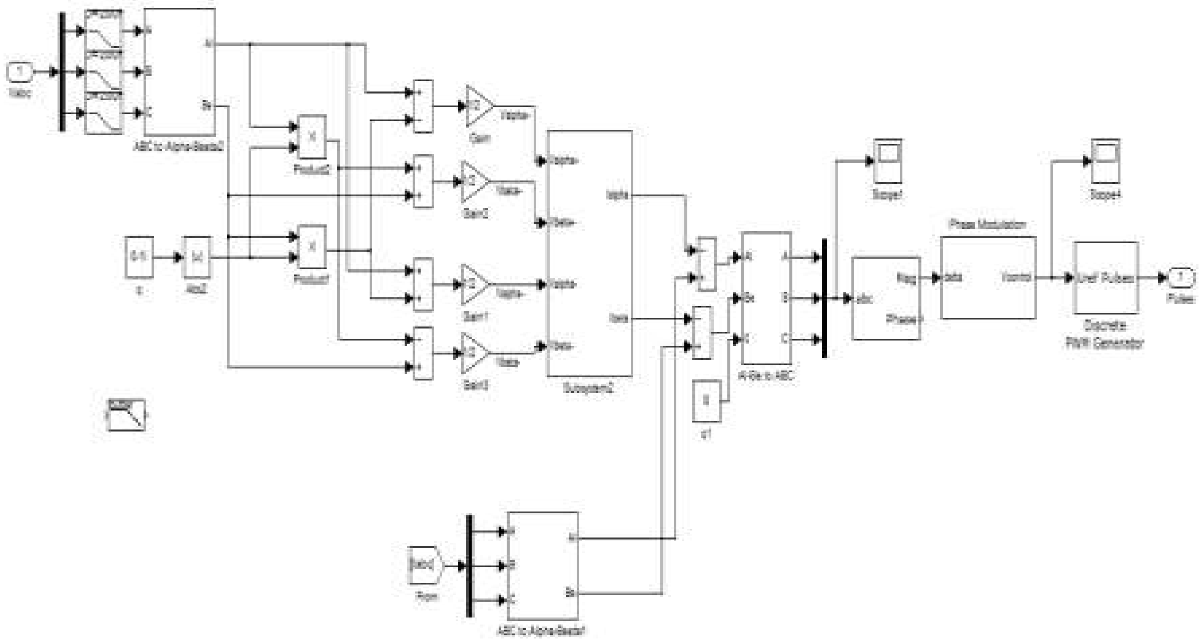

Fig. 7: Controller with signal

RESULTS AND DISCUSSION

Replication of the proposed test system is built using MATLAB/Simulink tool. Modelling of each component in detail is shown in this section. To start with, the source, inverter, its control unit and their associated simulated results are shown followed by the entire system model. Figure 4 gives the simulation model of the entire system. And each of its functional elements are given below along with its outputs are shown. The inverter projected in this study is a three-phase cascaded seven-level inverter whose model for single phase is shown in Fig. 5 due to space constraints. Similar model is used for the other two phases. It could be noted that each level requires an individual source here a PV source is used. The three-phase voltage from the inverter is given in Fig. 6.

Secondly, the control for the inverter is modelled using (21) and (22) which was discussed earlier. The control voltage from the controller is used to generate the required pulses using carrier based pulse width modulation. Figure 7 shows the controller along with the control signal in Fig. 8.

The entire model of the proposed test system is given in Fig. 4 and the overall results are shown in subsequent figures. Figure 9 represents the input voltage and current generated by the seven-level inverter to serve the load. The next figure, Fig. 10 represents the grid voltage and current which shows a balanced three-phase fault in the grid. Finally Fig. 11 corresponds to the load voltage and current at the PCC. It is apparent that the control algorithm has supported in rectifying the sag which proves the effectiveness of it. Similar results were obtained during the occurrence of faults in a phase or two.

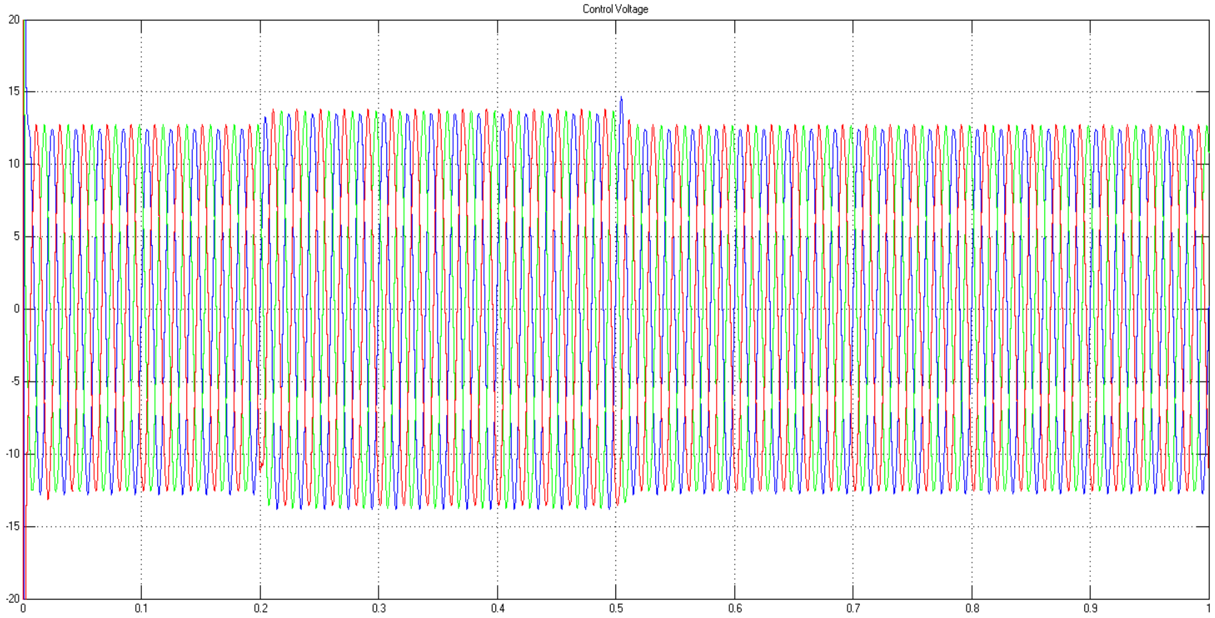

Fig. 8: Control signal from controller

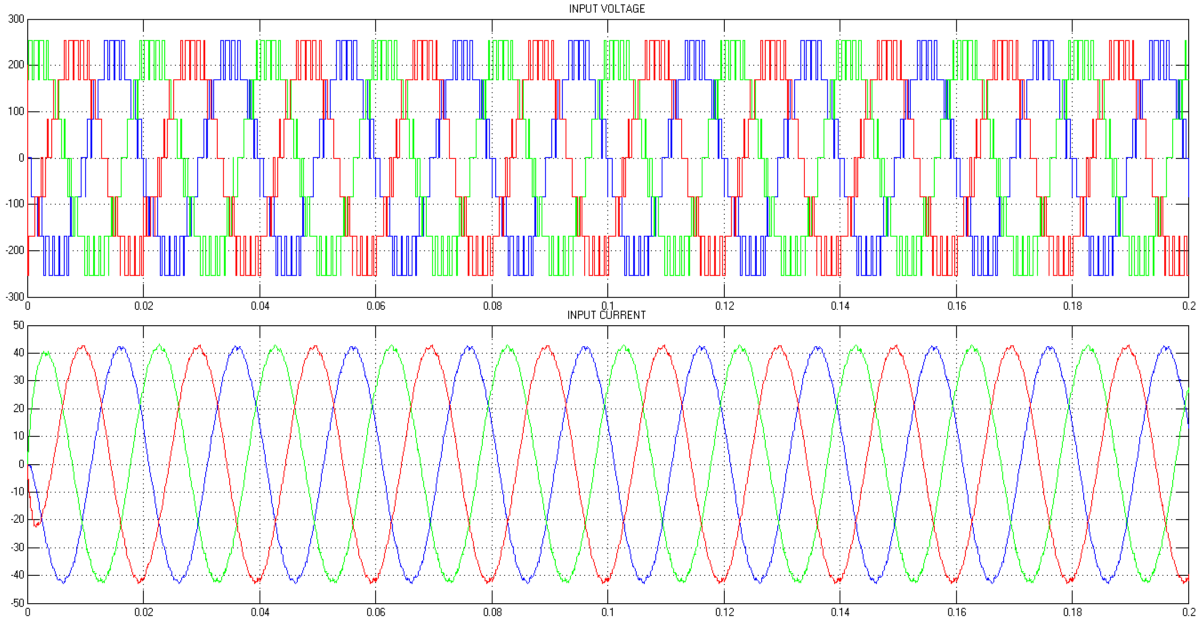

Fig. 9: Voltage to the grid from inverter

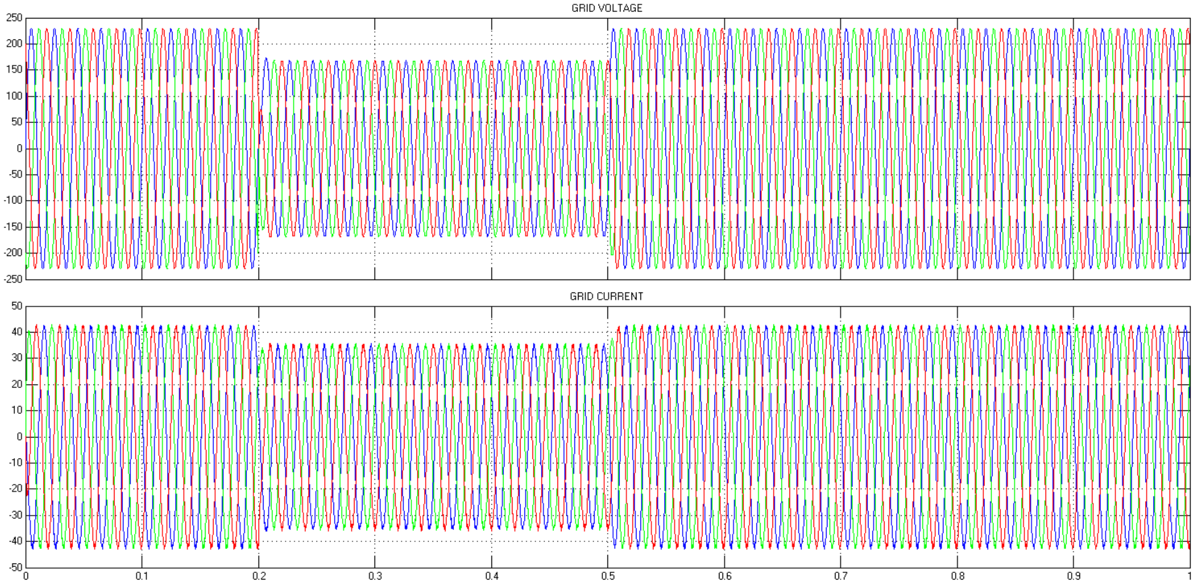

Fig. 10: Three-phase balanced voltage sag in grid

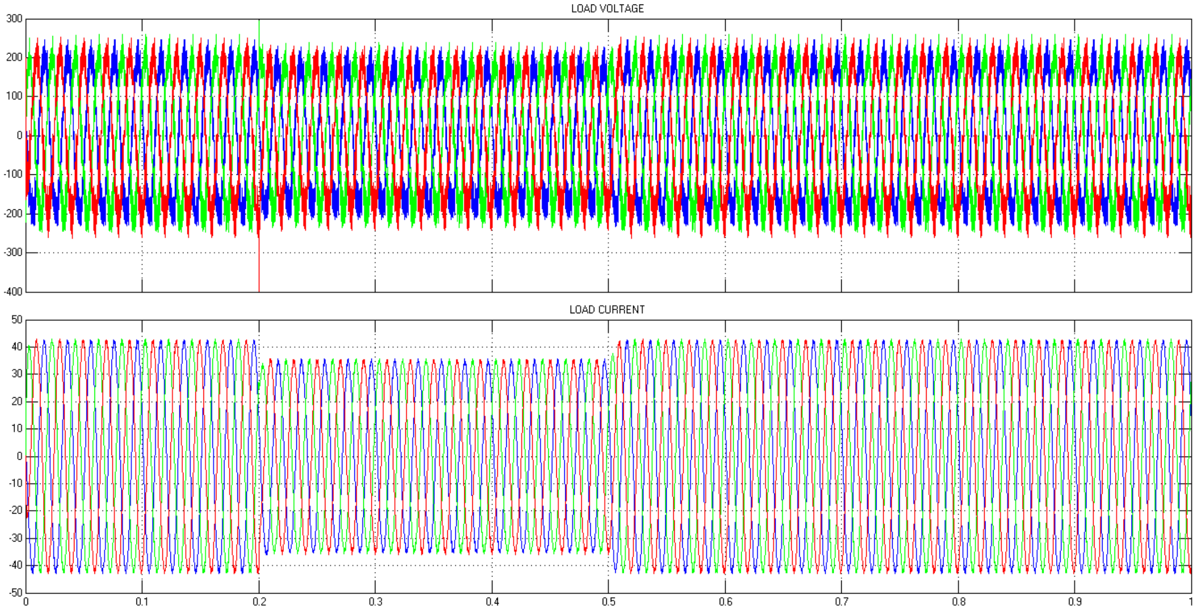

Fig. 11: Corrected load voltage at PCC

CONCLUSION

The proposed control algorithm described in this study provides a flexible voltage control from that of the conventional control. To bring out high order results a seven-level cascaded inverter is used. The control scheme is able to raise the voltage during three-phase balanced voltage sags, equalizes the voltage at the event of fault in a phase or two and a balance between the two states are possible. The above strategies are accomplished by tuning the control parameter. Its effectiveness is distinctive from the simulated results. Simulations are performed using MATLAB/Simulink tool. Future work includes adding higher levels to the inverter and use of space vector modulation over carrier based pulse width modulation for the multi-level inverter.

REFERENCES

Camacho, A., M. Castilla, J. Miret, J.C. Vasquez and E. Alarcon-Gallo, 2013. Flexible voltage support control for three-phase distributed generation inverters under grid fault. IEEE T. Ind. Electron., 60(4): 1429-1441.

Chattopadhyay, S., M. Mitra and S. Sengupta, 2011. Electric Power Quality. In: Chapter 2, Power Systems. Springer Science+Business Media, B.V., Netherlands.

Guerrero, J.M., J. Matas, L.G. de Vicuna, M. Castilla and J. Miret, 2007. Decentralized control for parallel operation of distributed generation inverters using resistive output impedance. IEEE T. Ind. Electron., 54(2): 994-1004.

Guo, X., X. Zhang, B. Wang, W. Wu and J.M. Guerrero, 2014. Asymmetrical grid fault ride-through strategy of three-phase grid-connected inverter considering network impedance impact in low-voltage grid. IEEE T. Power Electr., 29(3): 1064-1068.

Hochgraf, C., R. Lasseter, D. Divan and T.A. Lipo, 1994. Comparison of multilevel inverters for static vAr compensation. Proceeding of the Conference Record of the 1994 IEEE Industry Application Society Annual Meeting, 2: 921-928.

KlempKa, R., 2008. Distributed system for power quality improvement. Electr. Pow. Qual. Utilisat. J, 14(2).

Rodriguez, P., A.V. Timbus, R. Teodorescu, M. Liserre and F. Blaabjerg, 2007. Flexible active power control of distributed power generation systems during grid faults. IEEE T. Ind. Electron., 54(5): 2583-2592.

Serban, E. and H. Serban, 2010. A control strategy for a distributed power generation microgrid application with voltage- and current-controlled source converter. IEEE T. Power Electr., 25(12): 2981-2992.

Suresh, K.S. and M.V. Prasad, 2012. Analysis and simulation of new seven level inverter topology. Int. J. Sci. Res. Publ., 2(4).

Villalva, M.G., J.R. Gazoli and E.R. Filho, 2009. Modeling and circuit-based simulation of photovoltaic arrays. Proceeding of the Brazilian Power Electronics Conference (COBEP'09). Bonito-Mato Grosso do Sul, Brazil, pp: 1244-1254.