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Open-Delta VSC Based Voltage Controller in Isolated Power Systems

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ABSTRACT

This paper proposes a reduced switch voltage source converter (VSC) topology implemented as a voltage controller in isolated power systems. In isolated power systems generally self-excited induction generators (SEIG) are used mainly for their ruggedness and economic reasons. Mostly for constant power applications such as pico hydro uncontrolled turbine driven self excited induction generators feeding three-phase loads are employed. The proposed reduced switch voltage controller is used to regulate and control the voltage at the generator terminals as it is subjected to voltage drops, dips or flickers when the isolated power system is subjected to various critical loads. In this paper the controller is realized using a three-leg four-switch insulated gate bipolar transistor (IGBT) based current controlled voltage-source converter (CC-VSC) and a self-supporting dc bus containing two split capacitors, thus reducing the IGBT count and hence cost. This reduced switch topology forms an Open-Delta type converter. The proposed generating system along with the controller is modeled and simulated in MATLAB along with Simulink and power system blockset (PSB) toolboxes. The system is simulated and the capability of the isolated generating system along with the reduced switch based voltage controller is presented here where the generator feeds linear and non-linear loads are investigated.

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1. INTRODUCTION

In remote locations, isolated generating units are being used to exploit the energy available from renewable energy sources namely solar, hydro or wind. These isolated power systems are dedicated to provide electrical power within a small local grid sited in far-flung villages or in inaccessible hilly terrains. As the transmission costs are high, these local power systems are a cost effective option and can be set-up with modest effort. Such micro or small isolated power networks generally comprises of a self-excited induction generators (SEIG) driven by prime movers deriving their energy from non-conventional sources. The induction machine being the obvious choice in such systems because of its low cost, rugged brushless construction, small size, low maintenance and self short circuit protection. The asynchronous machine when running as a generator are self excited by a capacitor bank connected across its terminals [1-8]. A detailed review and comparison is presented in [9]. These isolated power networks are vulnerable to voltage sag, dip or flicker due to various consumer load conditions such as: sudden increase in load, unbalanced loads and non-linear loads connected to the power network. In such a case the SEIG operation is subjected to uneven heat distribution and even torque ripples and as a result operates at a de-rated level which further affects the quality of power at the generator terminals which is also the point of common coupling (PCC) for other loads in the isolated system. To take care of such a situation i.e to improve the quality of power and supply sufficient reactive power to the system, the most effective solution is the use of a DSTATCOM as cited by various authors in [10-16]. DSTATCOM generated reactive power caters to the requirement of same as demanded by power system and its loads. Moreover it reduces the reactive power demanded by the capacitor bank (connected at generator terminals for excitation) to its no-load level [17]. DSTATCOM's are power electronic converters, bidirectional in its function and are able to serve multiple purposes of voltage regulation, suppress effect of poor power factor of loads on power systems, reduce effects of unbalanced loading and also load leveling (if some energy storing components are provided). Generally a DSTATCOM is realized using a current controlled VSC comprising of six power switches, a DC bus capacitor and filter inductors in each line.

The objective of the paper is to use a reduced switch converter topology (four-switch) christened as Open-Delta (one converter leg devoid of active switches) voltage source converter (OD-VSC) to perform the task of a six switch DSTATCOM. This reduced switch converter topology has been used in number of research works, majority of which is in the area of machine drives for induction motor drives [18], and more recently in brushless BLDC drives as in [19-20] and in synchronous motor drives [21]. In view of its low converter cost, because of reduced requirement of switches, heat sink and driver circuitry, this topology has generated much interest among the authors to utilize it as a voltage controller for autonomous power systems. Thus, this paper proposes an application area for the low cost reduced switch converter topology for voltage regulation against transient fluctuations in voltage profile under various loading conditions occurring in an off-grid isolated power system. This OD-VSC topology comprises of four active switches instead of six and two numbers of capacitors at the DC bus [18-29]. The cost of semiconductor, heat sink and driver circuit is reduced by $1/3^{rd}$ due to changed topology of the converter circuit. The isolated distribution system under study has the following components: a SEIG thriving on constant power delivered by a micro-hydro turbine and an OD-VSC controller with a battery energy storage system (BESS) at the DC side. The OD-VSC controller takes care of voltage flickers, drops and sags occurring in the power distribution system due to various loading conditions. In a constant speed turbine driving the asynchronous frequency is maintained constant due to constant speed of prime mover. In this paper, the system is simulated in MATLAB Simulink Version 7.9 which comprises of an OD-VSC controller connected at the PCC, where power is generated by the SEIG fed by a constant power input. The effectiveness of the OD-VSC based controller is validated with simulation results for various types of connected loads: a) Balanced Linear and non-linear loads b) Unbalanced Linear and Non-linear loads.

2. POWER SYSTEM LAYOUT

The layout of the power system is depicted in Figure 1. It comprises of a three-phase asynchronous generator driven by a constant speed prime-mover. The generated power is delivered to the dedicated power distribution system (isolated from the main grid) with various consumer loads such as balanced, unbalanced, linear and/or non-linear.

Three star connected static capacitors are also provided for supplying the no-load exciting current of the asynchronous generator. The OD-VSC BESS type controller is as shown, connected in shunt to the power network at the point of common coupling in Figure 1. Four power-switches (IGBT's) and two capacitors form the main power circuit of the controller. The DC bus consists of two split capacitor, the midpoint of which is connected to one phase of the AC side. A BESS is connected across the DC bus. The battery is modeled with a parallel combination of a considerably high value capacitor (C_B) and a resistance (R_B) and a small value series resistance (R_s). This battery serves as a power source during operation of the DSTATCOM as a current-controlled voltage source inverter. The AC side terminals of the OD-VSC configured converter terminals are connected to the SEIG terminals. Three filter reactors with inductance L_f and resistance R_f are used to replicate the effect of a of the transformer inductive reactance as that of a practical system.

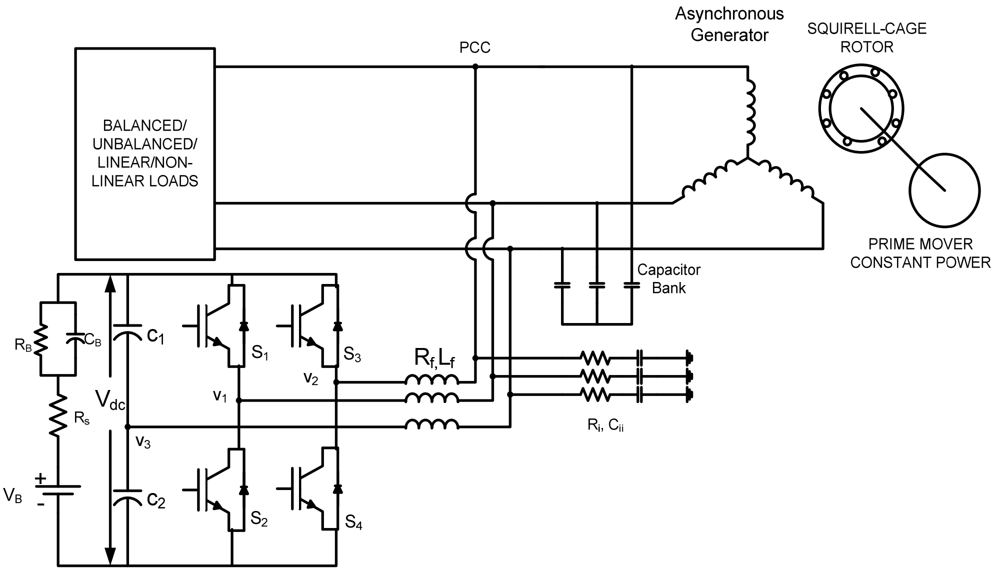

Figure 1. Power System Layout diagram of the isolated power system

3. OPERATIONAL CONTROL STRATEGY

The main aim of a voltage and frequency controller is to regulate the voltage of a power system under severe loading conditions. More precisely it is used to control the reactive power flow (injected or absorbed) in a power system and consequently keep a check on the terminal voltage at the point of common coupling (PCC) which is the common distribution point to various consumer loads. The VSC system is commanded (by its controller) to absorb reactive power if it sees its terminal voltage rises above the prescribed value whereas it injects reactive power into the system when the voltage drops. In this paper a reduced switch PWM converter OD-VSC is controlled to deliver the similar attributes of a conventional six switch DSTATCOM. Load balancing, load leveling and harmonic reduction functions are also contributed by the reduced switch solid-state controller. The control scheme shown in Figure 2 comprises of two outer loops for voltage control: one for maintaining DC bus voltage and the other for monitoring the AC side terminal voltage of the VSC. The direct axis current reference (I_{gdref}), the active current component, is generated from the DC bus voltage error processed through a PI controller block. The DC bus voltage (V_{dc}) is essentially the sum of the individual voltages across the capacitors C_1 and C_2 as represented in Figure 1. The reactive current component (I_{gqref}) is obtained after processing the error of the AC side terminal voltage at the PCC.

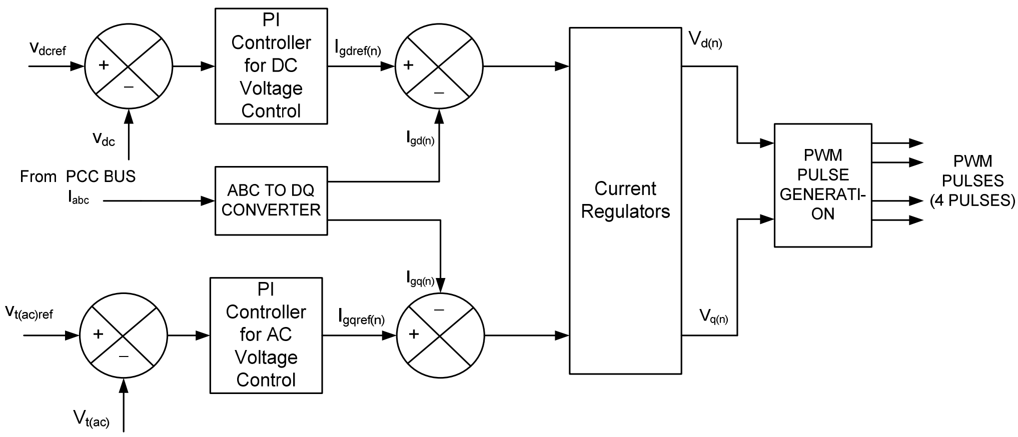

Figure 2. Control block diagram

AC side terminal voltage ($V_{t(ac)ref}$) is set at a reference value of 1 p.u. The synchronization of the positive sequence voltage components of the three phase supply side AC voltages is achieved with the help of a phase-locked-loop (PLL). The three-phase line currents of the power system are sensed, measured, and finally converted to 'd-axis' and 'q-axis' components by getting required synchronizing signals from the PLL. The current regulators generates the respective d-axis voltage term $V_{d(n)}$ and q-axis voltage term $V_{q(n)}$, which are fed to the PWM generation block. As this topology has four active power switches so only four PWM signals are to be generated to operate those switches in a fashion to control the reactive power and attain zero voltage regulation.

4. CONTROL ALGORITHM THEORY

Assuming the line voltages at the generator terminals to be purely sinusoidal and balanced three-phase AC voltages, the amplitude of this voltage can be obtained from the three line-to-line voltages v_{ab}, v_{bc}, v_{ca} and thus can be expressed as:

$$V_{t(ac)ref} = \sqrt{(2/3)(v^2_{ab} + v^2_{bc} + v^2_{ca})} \quad (1)$$

The quadrature component of desired reference source current is computed from the voltage error which is difference between the desired terminal voltage $V_{t(ac)ref}$ and $V_{t(n)}$, the measured voltage at nth instant of the AC source terminal computed from equation in (1). This voltage error $V_{er(n)}$ at the nth sampling instant is given in (2),

$$V_{er(n)} = (V_{t(ac)ref} - V_{t(n)}) \quad (2)$$

The reference quadrature component of current is given by,

$$I_{gqref(n)} = I_{gqref(n-1)} + K_{pa}\left\{V_{er(n)} - V_{er(n-1)}\right\} + K_{ia}V_{er(n)} \quad (3)$$

K_{pa} and K_{ia} in equation (3) are the proportional and integral gain constants of the outer PI controller (controller 'a'). $V_{er(n)}$ and $V_{er(n-1)}$ are the voltage errors at nth and (n-1)th instants. $I_{gqref(n-1)}$ is the quadrature current component at (n-1)th instant.

The q-axis current of the system is derived after sensing the three-phase source currents and converting them to d-q currents by Park's transformation. Thereafter the I_{gqref} and the calculated q-axis source current are fed into a current controller block as shown in Figure 2. The current error at nth instant is calculated as,

$$I_{gqer(n)} = (I_{gqref} - I_{gq(n)}) \quad (4)$$

This current error is processed through a inner PI controller to generate the d-axis desired voltage reference $V_{q(n)}$ given as below in (5),

$$V_{q(n)} = V_{q(n-1)} + K_{pb}\left\{I_{gqer(n)} - I_{gqer(n-1)}\right\} + K_{ib}I_{gqer(n)} \quad (5)$$

K_{pb} and K_{ib} are the proportional and integral gains for the inner PI controller (controller 'b') of the current control block.

To maintain the DC bus voltage at the reference DC bus voltage level, the DC bus voltage error is computed as in (6) and this error being again fed to a PI controller block.

$$V_{dcer(n)} = (V_{dcref} - V_{dc(n)}) \quad (6)$$

From the DC voltage error obtained at any instant i.e sampled at 'n', the requisite in-phase or active current component $I_{gdref(n)}$ at 'n th sample time can be obtained as,

$$I_{gdref(n)} = I_{gdref(n-1)} + K_{pa}\left\{V_{dcer(n)} - V_{dcer(n-1)}\right\} + K_{ia}V_{dcer(n)} \quad (7)$$

K_{pa} and K_{ia} are the proportional and integral gains for the inner PI controller of the current controller. The d-axis source current at the nth instant $I_{gd(n)}$ as obtained after Park's transformation from the sensed three-phase currents of the AC source, is used to get the d-axis current error $I_{gder(n)}$ given as in (8),

$$I_{gder(n)} = (I_{gdref(n)} - I_{gd(n)}) \tag{8}$$

$I_{gdref(n)}$ is the calculated values of reference current at the nth instant.

$$V_{d(n)} = V_{d(n-1)} + K_{pb}\left\{I_{gder(n)} - I_{gder(n-1)}\right\} + K_{ib} I_{gder(n)} \tag{9}$$

The d-axis voltage is then obtained according to (9) in the PI controller as in Figure 2. K_{pb} and K_{ib} are the proportional and integral gains for the inner PI controller.

5. PWM STRATEGY

The PWM strategy is sinusoidal pulse-width modulation technique, although because of the changed topology of the VSC, in this case, some changes needs to be incorporated. The modulation index 'm' and the phase angle 'Φ' are computed from $V_{d(n)}$ and $V_{q(n)}$ which has been derived at (9) and (5) respectively. From 'm' and 'Φ' the desired sinusoidal signals are derived for SPWM control. A high switching frequency triangular signal is used to attain the four switching signals of the IGBT's. The control block diagram for implementation of SPWM for Open-Delta converter is depicted in Figure 3. The transformed signals from reference set of voltages v_1, v_2, v_3 as shown in Figure 1 and given in (10) through (12) are used to obtain the modulating waveforms for sinusoidal PWM. Two signals (v_1 - v_3) and (v_2 - v_3) are processed to achieve two symmetrical voltages reference waveforms for phases 1 and 2 which are sinusoidal waveforms phase displaced by 60^o from each other with a peak value $\sqrt{3}$ times of that of desired phase voltages.

$$v_{10} = v_1 - v_0 = \sqrt{3} V_m Sin\left(\omega t - \frac{\pi}{6}\right) \tag{10}$$

$$v_{20} = v_2 - v_0 = \sqrt{3} V_m Sin\left(\omega t - \frac{\pi}{2}\right) \tag{11}$$

$$v_{30} = v_3 - v_0 = 0 \tag{12}$$

Phase-3 consists of no controllable switches thus the reference waveform for the third phase is zero. Subsequently the switching signals can be obtained by conventional comparison of the reference waveforms with a high frequency triangular carrier wave.

This technique has excellent features, like real-time control and easily obtained drive signals, the number of switching's are relatively high, and the reference signal should be synchronized to the carrier signal.

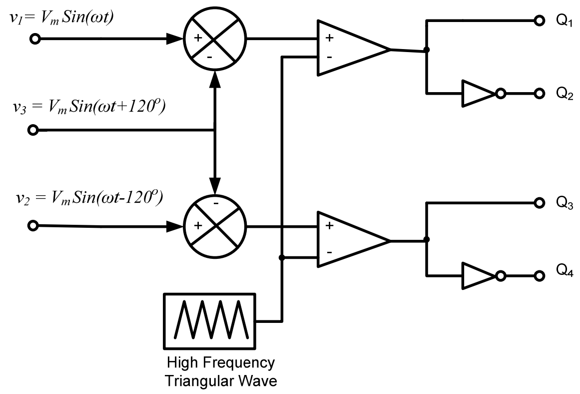

Figure 3. SPWM control of Open-Delta voltage source converter

6. DESIGN OF BESS CONTROLLER FOR OD-VSC CONTROLLER

Figure 1 shows the BESS where the battery has been modeled by its Thevenin's equivalent circuit. V_{dc} is the DC bus voltage, V_{oc} is the no-load open circuit voltage of the battery, R_s is generally of small value and is the equivalent resistance (external and internal) of the battery. The energy storage and voltage condition during charging and discharging is represented by the parallel combination of R_B and C_B. The value of R_B is large as the self discharging current of a battery is small. The dc bus voltage for a six-switch converter system should be greater than peak of the r.m.s line voltage at the ac side for proper operation of the VSC. For working with an Open-Delta converter the terminal voltage of battery is given by,

$$V_B = V_{dc} = 2\left(\frac{2\sqrt{2}V_{rms}}{\sqrt{3}m}\right) \tag{13}$$

'm' is the modulation index which can have a maximum value of 1.0. The line voltage on the AC side of the VSC is V_{rms}. The equivalent capacitance of the battery model can be mathematically represented by (14) given below,

$$C_B = \frac{kWh \times 3600 \times 10^3}{0.5(V_{oc\max}^2 - V_{oc\min}^2)} \tag{14}$$

where V_{ocmax} and V_{ocmin} are respectively the maximum and minimum open circuit voltage of the battery during its operation. Energy stored in the battery is measured in kWh.

7. MATLAB BASED MODELLING AND CONTROL

The entire system of Figure 1 is modeled in MATLAB 7.9 platform. Forward Euler method of integration is used for all integrations in the PI controller blocks. The discrete time integrator block approximates 1/s as T/(Z-1), which gives the expression for any output at n^{th} sample time/step Y(n) as,

$$Y(n) = Y(n-1) + \text{KT*U(n-1)} \tag{15}$$

A 15 kW, 415V, 50 Hz, 4-pole Y-connected induction machine is modeled to operate as an induction generator and 5-kVAR Y-connected excitation capacitor bank with neutral is connected at the three-phase terminals. The OD-VSC BESS based DSTATCOM is connected in shunt to the AC distribution system through transformer impedance L_f, R_f. The asynchronous generator feeds various consumers and thus is exposed to linear, non-linear, balanced and un-balanced loads. The performance of the Open-Delta based controller is tested for all these loading conditions to establish its efficacy. The system is realized using the models in Power System Block-set available in Matlab Simulink (version 7.9) and is simulated in discrete mode at 0.5 μsec step size with ode 23tb (stiff/TR-BDF-2) solver.

8. SIMULATION RESULTS AND DISCUSSION

The following measurements were made in the model: the voltage across induction generator that is also the voltage at the PCC (Vabc), induction generator current (iabc), load current (balanced/unbalanced/linear/non-linear) (ila, ilb, ilc) or (iLabc) , current through capacitor bank ic-abc, three-phase controller currents are ica, icb, icc, terminal AC voltage at the PCC (Vtm), induction generator speed (w), DC bus voltage (V_{dc}), battery current (ib).

8.1 Performance of System under Linear Loads with and without OD-VSC BESS Controller

The performance of an OD-VSC BESS based controller is presented in Figure 4. At 0.3 sec, balanced three-phase linear loads are connected to the PCC. The generator supplies the load showing increase in value of iabc. Voltage regulation aspect of the OD-VSC BESS based controller can be observed from the generator terminal voltage. At 0.4 sec one of phases of the linear inductive delta connected load is opened and at 0.6 sec another load phase is also opened, making the load completely unbalanced. At 0.55 second the controller is disconnected from the generator and now it has to run on its excitation provided by the capacitor bank. The voltage regulation property of the controller is no more in function as such the generator voltage drops as it is unable to sustain without the reactive power supply from the reduced switch DSTATCOM, it finally fails and decreases further. At 0.55 sec the controller current rises as it has to now supply the load currents due to failure of the controller. It is further reconnected to the generator terminals at 0.65 sec and voltage is again regulated at its previous value. The vabcc, the controller voltage is always controlled at the desired level and it supplies the load during the failure of the induction generator. This establishes the load leveling feature of the OD-VSC controller in this isolated network.

8.2 Performance of OD-VSC BESS Controller under Linear Loads

The system is started with balanced three-phase star connected inductive loads as shown in Figure 5. At 0.3 sec one of the phases is disconnected and at 0.4 sec another phase is disconnected. The three-phase SEIG terminal voltage vabc is regulated nearly at its rated set value and generator currents remain nearly sinusoidal during become highly unbalanced loading. The change in loading conditions is taken care of by the controller, as can be seen from the nature of controller currents, change in battery current and the ripples in the DC bus voltage during the time interval 0.3 sec to 0.5 sec.

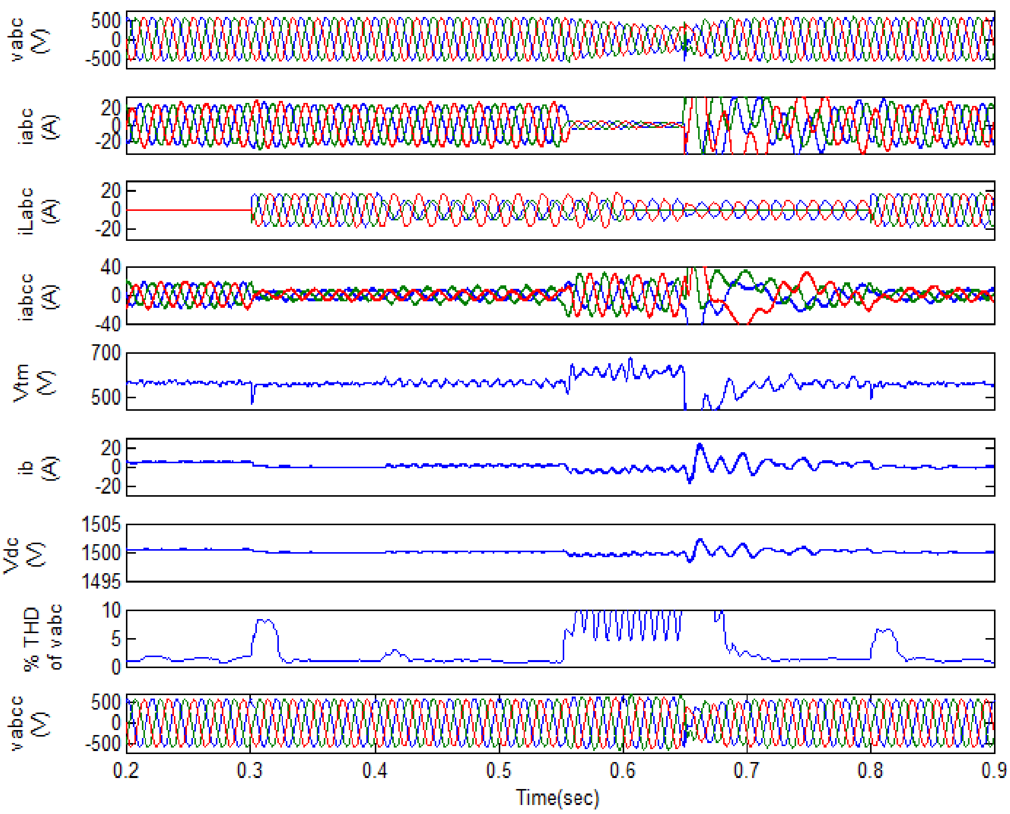

Figure 4. Performance of OD-VSC BESS based voltage controller

The generator currents remain constant shown by iabc. All loads are reconnected at 0.5 sec. The terminal voltage magnitude V_{tm} is close to its reference value. The load is switched off at 0.8 sec and the BESS charges up as shown by battery current ib, from the excess power available from the generator.

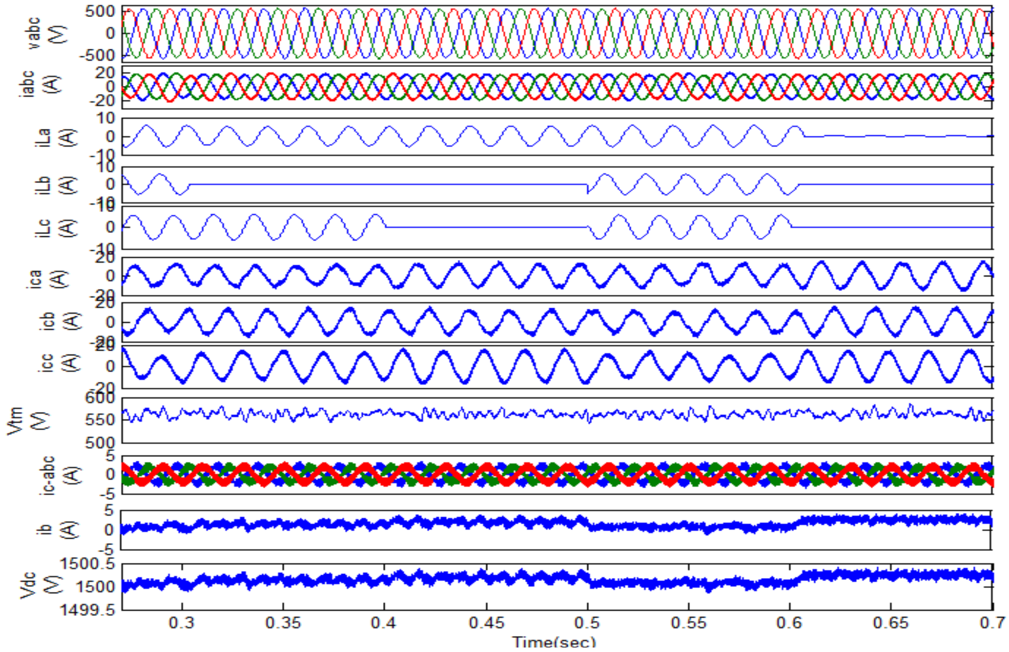

Figure 5. Performance of OD-VSC based DSTATCOM with linear loads (balanced/unbalanced)

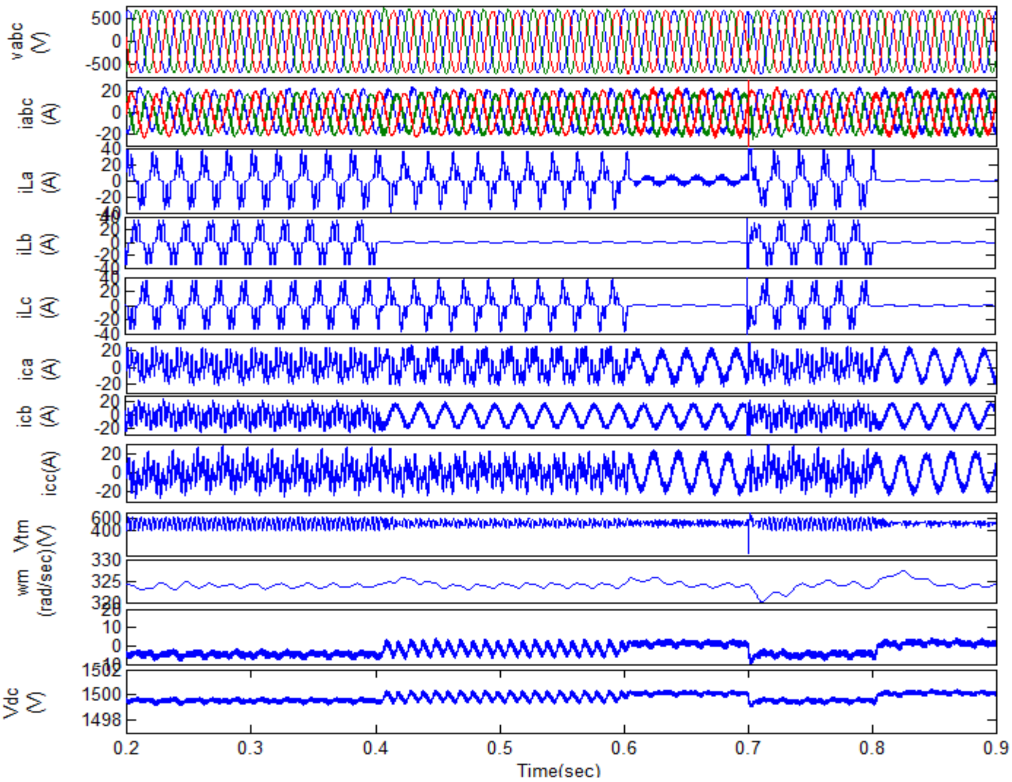

Figure 6. Performance of OD-VSC based DSTATCOM with non-linear loads (balanced/unbalanced)

8.3 Performance of System under Non-Linear Loads

The proficiency of the Open-Delta based DSTATCOM is now tested with balanced/unbalanced non-linear loads and the results are presented in Figure 6. Three single-phase diode rectifier circuits are connected with respect to the source neutral as three-phase non-linear loads. Each single phase rectifier supplies 5 kW resistive load at the DC side and has filter capacitor connected across each rectifier load. The non-linaer load currents are shown as iLa, iLb and iLc. The controller currents ica, icb and icc are highly non-linear so as to compensate for the injected harmonics by the non-linear loads. At 0.4 sec one of the phases of the non-linear load is opened, whereas at 0.6 sec the other phase is also opened. During these unbalanced conditions the line currents at the generator side show minor imbalances due to the fact that one of the three-phase generator terminals is connected to the capacitor mid-point at the DC bus, but the generator currents are mostly sinusoidal waveforms. From 0.4 sec to 0.6 sec the DC bus ripples increases and indicates how the OD-VSC controller supplies the harmonic currents introduced in the system due to non-linearity of the load. The generator voltage remains almost steady at the reference magnitude Vtm under all such the above loading conditions. At 0.8sec all the non-linear loads are disconnected and the available excess power goes in charging the battery at the DC bus shown by battery current and DC bus voltage rise to its reference value.

9. PERFORMANCE COMPARISON OF PROPOSED CONTROLLER WITH STANDARD CONTROLLER

A comparison of performance results of the proposed reduced switch controller and existing standard topology based controller is indicated in Table 1. The results in Table 1 indicate that the % THD of the generator voltages and currents under different loading conditions are well within the IEEE standards. Although compared to a standard topology based DSTATCOM the % THD's are slightly higher but the advantage lies in the fact that it is obtained by reduction in IGBT's in the converter circuitry which brings about a reduction in overall system cost.

Table 1. Comparison of % THD for PCC voltage and source current for a DSTATCOM based on reduced switch topology and a standard inverter topology

Type of Load	% THD of Load Currents	% THD for Open-Delta Controller (4 –switch)		% THD for Standard Controller (6-switch)	
		Generator Voltage	Source current	Generator Voltage	Source current
Linear Balanced Load	2.5	1.88	2.98	0.25	0.66
Linear Unbalanced Load	3.8	1.7	4.37	0.31	1.04
Non-Linear Balanced Load	31	4.08	2.21	1.41	2.64
Non-Linear Unbalanced Load	68.11	4.78	2.3	1.57	2.67

System Parameters

(I) 15 kW, 415 V, 50 Hz, Y-connected 4-pole Asynchronous machine:- Stator resistance, $R_{s=}0.435\ \Omega$, rotor resistance, $R_r'=0.816\ \Omega$, Stator reactance $X_{s=}1.5\ \Omega$, rotor reactance, $X_r'=2\ \Omega$, Mutual Inductance, $L_{m=}0.134$ H, Moment of Inertia, J=0.1384 $Kg\text{-}m^2$

(II) OD-VSC BESS Controller Parameters:-IGBT based 2-arm bridge configuration, split capacitor 3rd arm of 3-phase converter:- Split Capacitors: $C_{1=}C_2=2200\ \mu F$, IGBT switching frequency=20 kHz, $R_f=0.004\ \Omega$, $L_f=7$ mH, RC Filter: 1 Ω in series with 200 µF, PI Controller Gain: $K_{pa=}0.05$, $K_{ia}= 0.02$, $K_{pb}= 0.05$, $K_{ib}= 2$, Battery Voltage, $V_B=1500$ V; $R_s=0.1\ \Omega$; $R_B=10\ K\Omega$; $C_B=25000\ \Omega$

(III) Prime Mover Characteristics: $T_{sh}=K_1 - K_2\omega_r$, $K_{1=}3100$, $K_{2=}2$

(IV) Linear: 3 kW, 200 VAR per phase (unbalanced load) and 3 kW, 200 VAR constant load; Non-linear: Three single phase bridge rectifier with 5kW resistive loads on DC side with filter capacitance 200 µF

10. CONCLUSION

The control, simulation and performance of an OD-VSC BESS controller operated to absorb or inject reactive power supply in an isolated power system fed from isolated induction generator is presented in this paper. The results obtained are quite satisfactory. The OD-VSC functions properly and regulates generator voltage however severe the load type may be. Any power system is subjected to linear and non-linear loads, single-phase loads cause severe unbalanced currents in the system, but it has been observed that the voltages at the PCC remains nearly sinusoidal and at its reference value, the current waveforms at the generator lines also retain their set values and are also closely sinusoidal in nature even when the loads are linear or non-linear type under balanced or unbalanced conditions. The controller uses lesser number of active devices, thus a good amount of reduction in cost in terms of IGBT's can be achieved with proper designing of such a controller. IGBT's count is lesser adding to savings of the system. This reduced switch DSTATCOM is also capable of providing harmonic reduction and load leveling.

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