# IMPROVING LOW VOLTAGE RIDE THROUGH CAPABILITY OF WIND GENERATORS USING DYNAMIC VOLTAGE RESTORER

**Gangatharan Sivasankar — Velu Suresh Kumar** *

The increasing wind power integration with power grid has forced the situation to improve the reliability of wind generators for stable operation. One important problem with induction generator based wind farm is its low ride through capability to the grid voltage disturbance. Any disturbance such as voltage dip may cause wind farm outages. Since wind power contribution is in predominant percentage, such outages may lead to stability problem. The proposed strategy is to use dynamic voltage controller (DVR) to compensate the voltage disturbance. The DVR provides the wind generator the ability to remain connected in grid and improve the reliability. The voltage dips due to symmetrical and unsymmetrical faults are considered for analysis. The vector control scheme is employed for fault compensation which uses software phase locked loop scheme and park dq0 transformation technique. Extensive simulation results are included to illustrate the control and operation of DVR.

K e y w o r d s: voltage dip, impact of dip, DVR, vector control, fault ride-through control, dip mitigation

## 1 INTRODUCTION

The Wind power integration with power grid has increased significantly. An important problem with induction generator based wind farm is the inability to stay connected to the grid during a fault due to its low voltage ride through capability [1]. Any disturbance such as dip may lead to wind generators outage due to reactive power needs to restore the internal magnetic flux once the fault is cleared [2]. Hence wind generators are usually disconnected from the grid for safety. In the past the wind power penetration was low in percentage, hence any outage may not affect the system stability. But in recent years wind generation is in rapid expansion and its contribution to grid is as do conventional generation plant [3, 4]. Hence any outage of wind generators may lead to power shortage and collapse the stability [5]. Even if failures do not occur, poor power quality increase generator losses and decrease the efficiency. To address these challenges good knowledge of wind generation dynamics and interaction with the power system becomes critical.

The most commonly encountered problem in the grid is voltage dip. Dips are characterised as reduction in rms voltage from 0.1 pu to 0.9 pu, which last from few milliseconds to few cycles. Voltage sags are mainly caused by short duration faults in the supply line, energising heavy inductive loads and starting of induction motors. Voltage dip is not only characterised as reduction in voltage magnitude milliseconds to a few cycles. Voltage dips but also cause change in phase which is described as phase angle jump $\delta$. The phase-angle jump manifests itself as a shift in zero crossing of the instantaneous voltage. Phase angle jump can cause a large transient at the beginning and end of the dip because the internal generator flux is out of phase with the voltage [6]. Hence mitigation of dip can only be a complete solution for the aforementioned problems [7]. There are several methods and techniques that use STATCOM, SVC for dip mitigation [8]. However use of DVR is an appropriate solution for dip and its related issues [9]. DVR is a power electronic controller that can protect the wind generators from disturbances and make wind farm to remain connected to the grid without loss of stability and guarantee the reliability of the system.

In this paper the effect of symmetrical and unsymmetrical voltage dip on fixed speed wind generators and the associated problems caused in the grids are discussed. The proposed strategy is to use dynamic voltage restorer (DVR) for voltage dip compensation by series voltage injection as shown in Fig. 1. Vector control scheme is employed to compensate for both voltage magnitude and phase jump [10]. The proposed DVR can also exchange real and reactive power demand of wind generator [11]. Matlab simulink is used for wind farm modelling and to realise DVR control strategies.

## 2 IMPACT OF VOLTAGE DIP ON INDUCTION MACHINE

The equivalent circuit representation of an induction machine, based on Thevenin's theorem is shown in Fig. 2 and the related Eqs. (1), (2) are Thevenin's voltage and resistance respectively [12].

$$U_{s1TH} = \frac{U_{s1}(\omega_1 L_m)}{\sqrt{R_s^2 + (\omega_1 L_{s1} + \omega_1 L_m)^2}}\,, \tag{1}$$

$$R_{sTH} = \frac{(\omega_1 L_m)^2 R_s}{R_s^2 + (\omega_1 L_{s1} + \omega_1 L_m)^2}\,. \tag{2}$$

The Fundamental ($h = 1$) slip component of the circuit is given as

$$S_1 = \frac{n_{s1} - n_m}{n_{s1}} = \frac{\omega_{s1} - \omega_m}{\omega_{s1}} \tag{3}$$

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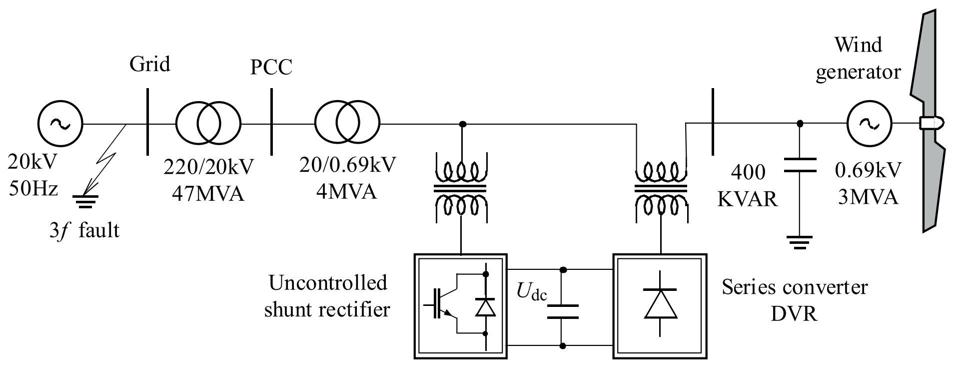


**Fig. 1.** Wind generator connected to grid with DVR protection

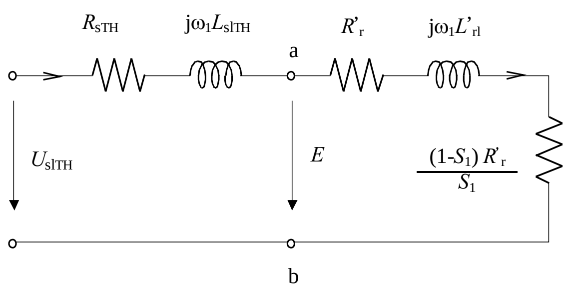


**Fig. 2.** Thevenin's equivalent circuit representation of an induction machine

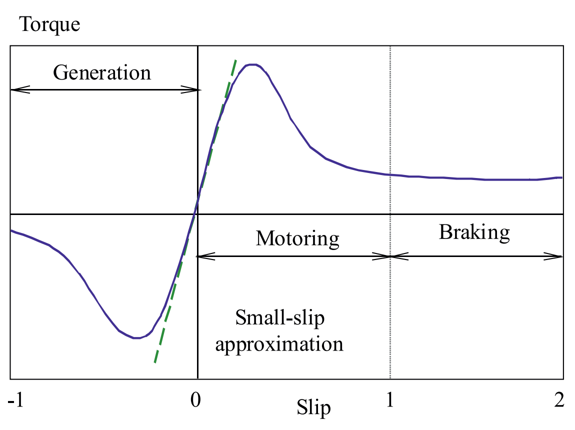


**Fig. 3.** Torque-slip characteristic curve with small-slip approximation

where $n_{s1}$ and $n_m$ are synchronous speed of the stator field and mechanical speed of the rotor respectively . And $\omega_{s1}$ and $\omega_m$ are the corresponding angular velocities. The value of the slip is considered as very small for FSIG and a small-slip approximation is done as show in Fig. 3.

The machine parameters for small slip value are derived as

$$T \approx \frac{1}{\omega_{s1}} \frac{3U_{s1TH}^2 s_1}{R_r'}, \tag{4}$$

$$P_{gap} = 3I_r'^2 \frac{R_r'}{s_1}, \quad P_{loss\,low} = s_1 P_{gap}. \tag{5,6}$$

Any change is line voltage affects the machine parameters. Hence the changes in machine parameters due to voltage dip are obtained as

$$P_{loss\,low} = \frac{s_{low}}{s_1} P_{loss\,rated} \tag{7}$$

where $s_{low}$, $P_{loss\,rated}$ is the slip and its power loss during voltage dip. The slip value increases during a dip, since it is inversely proportional to voltage as depicted in (4). The power loss increases predominantly with increase in slip (7), hence enormous heat is evolved during voltage dip. The impact of dip on torque with respect to slip is shown in Fig. 4.

## 3 SERIES VOLTAGE COMPENSATION FOR DIP MITIGATION

A series voltage compensation [13] scheme is illustrated using the equivalent representation as shown in Fig. 5. The grid voltage source $U_g$ and the wind generator voltage source $U_{wg}$ are integrated in parallel. The dip mitigation is done by insertion of compensation voltage $U_c$ in series between the voltage sources. The compensation voltage $U_c$ is supplied by DVR which is a voltage source inverter.

The series compensator takes the following steps for mitigation.

$$U_{wg} = U_g(t) + U_c(t). \tag{8}$$

The compensating voltage $U_c(t)$ must cancel the imbalance of the system voltages to obtain balanced voltages at the wind generator terminals; therefore,

$$U_{co} = -U_{go}, \quad U_{c-} = -U_{g-}. \tag{9}$$

The positive-sequence magnitude of the wind generator voltage $U_{wg}$ should be set to the desired regulated voltage. A series compensator is an injected positive-sequence voltage ($|U_{c+}|$). The $U_{c+}$ must have a phase difference of 90° with $i_{g+}$, since the grid current flows through the series compensator. This result in

$$U_{wg+} = U_{g+} + U_{c+}(a + jb) \tag{10}$$

where $(a + jb)$ is the unit vector which is perpendicular to $I_{g+}$. Assuming $U_{wg+} = U_{wg} < 0°$ (10) results in the following second-order equation

$$|U_{c+}|^2 - 2a|U_{wg}|\,|U_{c+}| + |U_{wg}|^2 - |U_{g+}|^2. \tag{11}$$

When the desired regulated voltage $U_{wg}$ is achieved, (11) will result in two real solutions for $|U_{c+}|$. The minimum solution is chosen for smaller rating of the DVR.

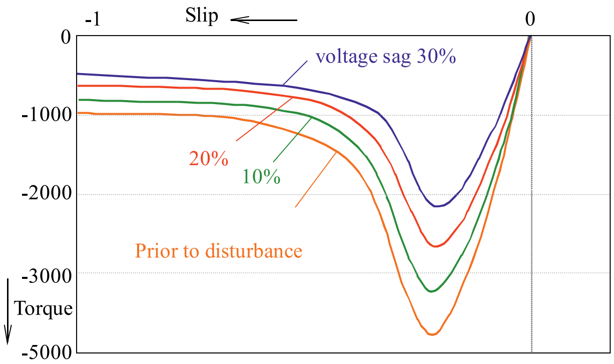


**Fig. 4.** Impact of dip on Torque-slip characteristic

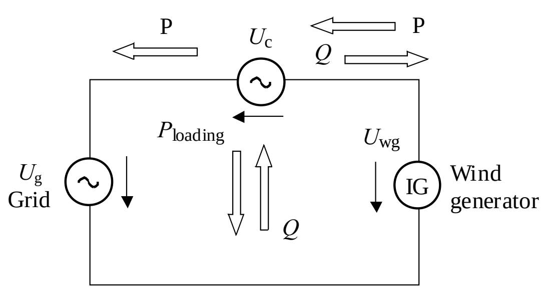


**Fig. 5.** Power flow representation during voltage dip compensation

## 4 CONTROL OF THE DVR

The considerations for control of the DVR include reference voltage generation, control of injection voltage, real and reactive power exchange and protection of DVR. A high performance control is required for a grid integration system. Hence vector control scheme is employed for control of the DVR as shown in Fig. 6. A vector-controller generates continuous control signals for instantaneous current and voltage values to be controlled in a system.

### 4.1 Reference Voltage Generation

The controller has to generate a accurate reference voltage for successful compensation. Software phase locked loop (SPLL) circuit is used for synchronization of the system [14]. Frequency adaptive performance, low computational burden and relatively high filtering capability are the advantages of this method, which make it a successful solution for voltage distorted and frequency-varying conditions. Figure 7 illustrates the general structure of the SPLL, in which $U_{g(abc)}$ is the input voltage, $\omega_d$ and $\theta_d = \omega_d t + \phi$ are the estimated frequency and angle respectively. $\omega_{ff}$ is the nominal frequency. Using $\alpha - \beta$ transformation $U_\alpha$ and $U_\beta$ are obtained which are in-phase and quadrature-phase components respectively. The control scheme uses Park $(dq0)$ transformation to obtain $d$–$q$ component, which is a widely used transformation. It is applied for time-dependent arbitrary three-phase system which is used to decouple variables and refer to common reference frame. The grid voltage may contain negative and zero-sequence components due to unbalanced voltage. For categorising the sequence components the system voltage is transformed into the synchronous $dq0$ reference frame. For an unbalanced voltage, the Park transformation results in

$$[U_d \quad U_q \quad U_o]^\top = \sqrt{\frac{2}{3}}\times \begin{bmatrix} \cos\theta_d & \cos(\theta_d - \frac{2}{3}\pi) & \cos(\theta_d + \frac{2}{3}\pi) \\ -\sin\theta_d & -\sin(\theta_d - \frac{2}{3}\pi) & -\sin(\theta_d + \frac{2}{3}\pi) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} U_{ga} \\ U_{gb} \\ U_{gc} \end{bmatrix} \tag{12}$$

$$= \sqrt{\frac{3}{2}} \left\{ \begin{bmatrix} U_{gp}\cos\phi_p \\ U_{gp}\sin\phi_p \\ 0 \end{bmatrix} + \begin{bmatrix} U_{gn}\cos(2\omega t + \phi_n) \\ U_{gn}\sin(2\omega t + \phi_n) \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ U_{g0}\cos(2\omega t + \phi_0) \end{bmatrix} \right\}$$

$$= \begin{bmatrix} U_{dp} \\ U_{qp} \\ 0 \end{bmatrix} + \begin{bmatrix} U_{dn} \\ U_{qn} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ U_{00} \end{bmatrix} \tag{13}$$

Where $\phi_p$ is the phase difference between the positive sequence component and the reference voltage. Hence, for a small phase difference, $U_d$ yields an estimation of the input voltage amplitude and $U_q$ gives the phase error information. The phase detector (PD) output signal $U_q$ is passed through the loop filter LF to attenuate the high-frequency noises. The LF here is a proportional-integral (PI) controller. The nominal value of the fundamental frequency $\omega_{ff}$ is then added to the LF output signal for accelerating the initial lock-in process and to reduce the control effort. The resulting signal $\omega_d$ is integrated afterwards to generate the estimated angle $\theta_d$. Then the vector controller calculates the values of grid voltage $U_q$ and wind generator voltage $U_{wg}$ in $d$–$q$ coordinates as $U_{g(d\text{–}q)}$ and $U_{wg(d\text{–}q)}$. Then according to (13), the dc components ($U_{gp}\cos\phi_p$ and $U_{gp}\sin\phi_p$) are obtained from the positive sequence component of the $dq0$ reference frame. Hence the $U_{dp}$ of (13) is maintained at $U_M$ and all other components are eliminated by the compensation voltage. As a result the reference voltage is obtained as shown below.

$$U^{ref}_{(d\text{–}q)} = \big[T_{(d\text{–}q)}(\cos\theta_d)\big]\, U^{ref}_{abc} = \begin{bmatrix} U_m \\ 0 \\ 0 \end{bmatrix} \tag{14}$$

where $U^{ref}_{abc} = \begin{bmatrix} U_g\cos(\omega t) \\ U_g\cos(\omega t + 120) \\ U_g\cos(\omega t - 120) \end{bmatrix}$.

The voltage dip detection is carried out by comparing the grid voltage with the reference voltage to obtain the value of the setting voltage $U^{ref}_{DVR(d\text{–}q)}$ to be generated in the DVR, so that the restored wind generator voltage reaches its nominal value.

$$U^{ref}_{DVR(d\text{–}q)} = U^{ref}_{d\text{–}q)} - U_{g(d\text{–}q)}\,. \tag{15}$$

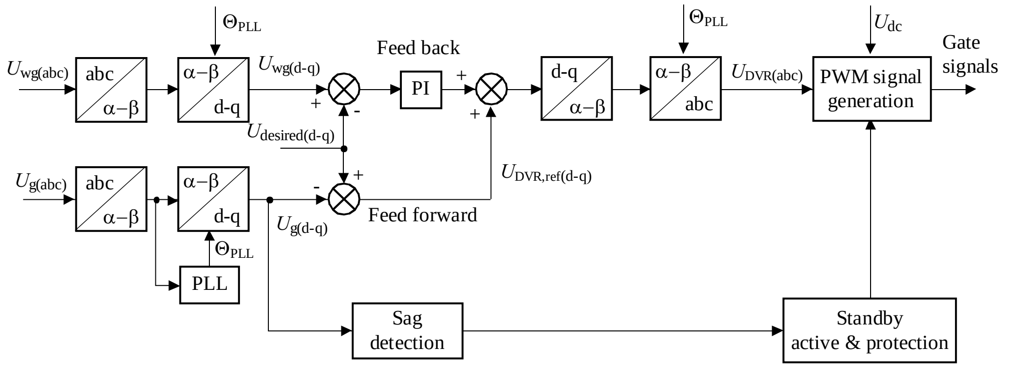


**Fig. 6.** Vector control in the rotating $dq$ reference frame

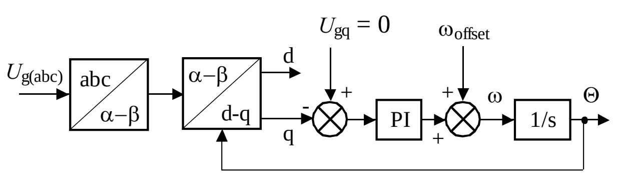


**Fig. 7.** Software Phase looked loop circuit

The $U^{ref}_{DVR(d\text{–}q)}$ reference voltage of (15) is then inversely transformed into the *abc* reference frame.

### 4.2 Control of Injection Voltage

The control of injection voltage is done by the combination of grid voltage feed-forward and PI *d–q* wind generator voltage feedback. Due to the inverter's output filter, there is a difference between the voltage generated with the inverter and the voltage actually injected in series with the line, so a PI regulator is used for equalization. The regulator output is added to DVR reference, serving as feed forward to improve the system response speed and uses the dc-link voltage to calculate the required modulation depth to inject the difference between grid voltage and the reference voltage. Finally, a sinusoidal pulse width modulation (SPWM) is used for the inverter switching.

### 4.3 Real and Reactive Power Exchange

The fault ride through capability of wind generator not only affect by voltage disturbance but also due to power dearth. The proposed DVR is capable of providing real and reactive power support. The uncontrolled shunt rectifiers are used to maintain a strong dc link which acts as a source to meet the real power demand. The reactive power compensation is done by switching the series converter in appropriate phase angle.

### 4.4 DVR Protection System

The series connected DVR inverter may face severe problem due to transients or fault current in the grid. And there is a chance of high in-rush of current reflects in to DVR, if the dip is not completely compensated. A proper protection of DVR inverter is one of the important aspects of the design which can be done using the design scheme presented in [15].

## 5 RESULTS AND DISCUSSION

In this section, two different fault cases are considered for compensation. In case I, voltage dip due to symmetrical three-phase to ground fault is investigated and it is assumed that there is no phase jump. The dip mitigation is done by in phase voltage insertion. In case II unbalanced dip due to unsymmetrical phase-to-phase grounded fault is investigated.

The positive sequence magnitude during fault is obtained by comparing nominal grid voltage as reference and negative sequence is compared to zero. There is no zero sequence, because the grid neutral is not connected. The reference signal to DVR consists of two sequence parameters one is in-phase positive sequence and the other is in phase opposition to the negative sequence. With the combination of two sequence components DVR inserts a three-phase voltage in series with the line to restore the balance of wind generator.

### 5.1 Three-Phase-to-Ground Fault and Mitigation

A three-phase-to-ground fault is evolved near the grid which starts at 500 ms and lasts for about 100 ms causing 40 % voltage dip at grid is shown in Fig. 8(a). The effect of fault on wind generator was synthesised by *d–q* component. Since it is a balanced fault, only positive sequences are represented, as depicted in Fig. 8(b). The real and reactive power at point of common coupling PCC is depicted in Fig. 8(c). The real power contributed by the wind farm to the grid is limited by the fault and the reactive power supplied to the wind farm is also restricted as shown in Fig. 8(d). If the dip is very deep and last for long duration the wind generators will be tripped and isolated from the network and this leads to stability problem. In such cases dip mitigation is the only solution to avoid aforementioned problem and to make the generator stay connected with the system.

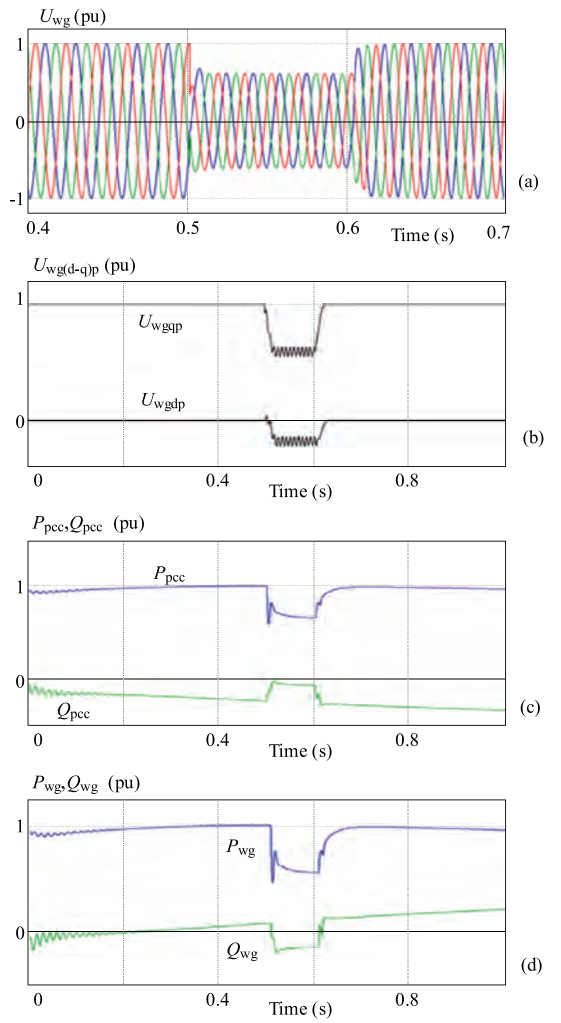


**Fig. 8.** The grid connected wind generator during three-phase-to-ground fault a – voltage dip b – positive sequence components c – active and reactive power at PCC d – active and reactive power at wind generator

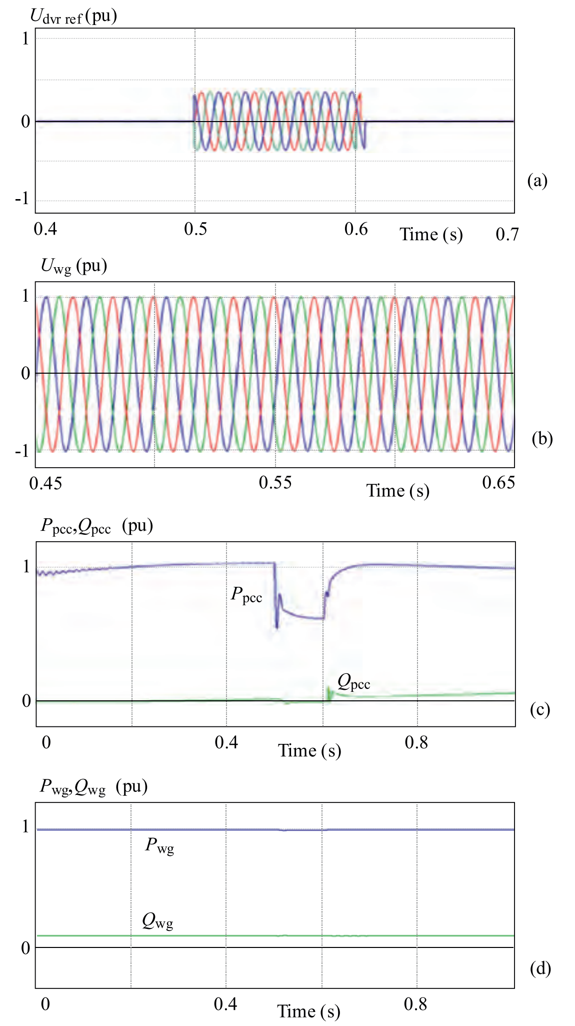


**Fig. 9.** The grid connected wind generator after three-phase-to-ground fault compensation a – DVR reference signal b – compensated voltage c – active and reactive power at PCC d – active and reactive power at wind generator

Using the vector control strategy, voltage dip magnitude was calculated and DVR compensation voltage is generated as shown in Fig. 9(a). The dip is compensated by an in-phase insertion of voltage in series with the line. Figure 9(b) shows the compensated voltage of the wind generator. Equipping the wind form with DVR not only mitigate the dip but also exchange reactive power demand of the wind generator. Hence the reactive power demanded from the source is greatly reduced. The series connected DVR consumes a loading power which further reduces the power in PCC as shown in Fig. 9(c). The real and reactive power at wind generator bus after compensation of three- phase-to-ground fault is depicted in Fig. 9(d).

## 5.2 Phase-to-Phase Grounded Fault and Mitigation

Unbalanced dip is realised using phase-to-phase grounded fault near grid. The voltage variation at wind generator is as shown in Fig. 10(a). The $d$–$q$ components of positive and negative sequences of wind generator bus during fault condition are obtained as shown in Fig. 10(b) and Fig. 10(c). The real and reactive power at PCC during phase- to- phase ground fault is as shown in Fig. 10(d). Figure 10(e) shows the real and reactive power at wind generator bus during the fault.

The compensation algorithm was same as the previous section and DVR reference signal is shown in Fig. 11(a). The reference signal to DVR consists of two sequence parameters one is in-phase positive sequence and the other is in phase-opposition to the negative sequence. With the combination of two sequence components DVR inserts a voltage in series to restore the balance of wind generator. Hence generator voltage level is restored and balance is maintained. Figure 11(b) shows the voltage level after the compensation and Fig. 11(c) shows the real and reactive power at PCC during compensation. Real and reactive power at wind generator bus after compensation of phase-to-phase ground fault is show in Fig. 11(d).

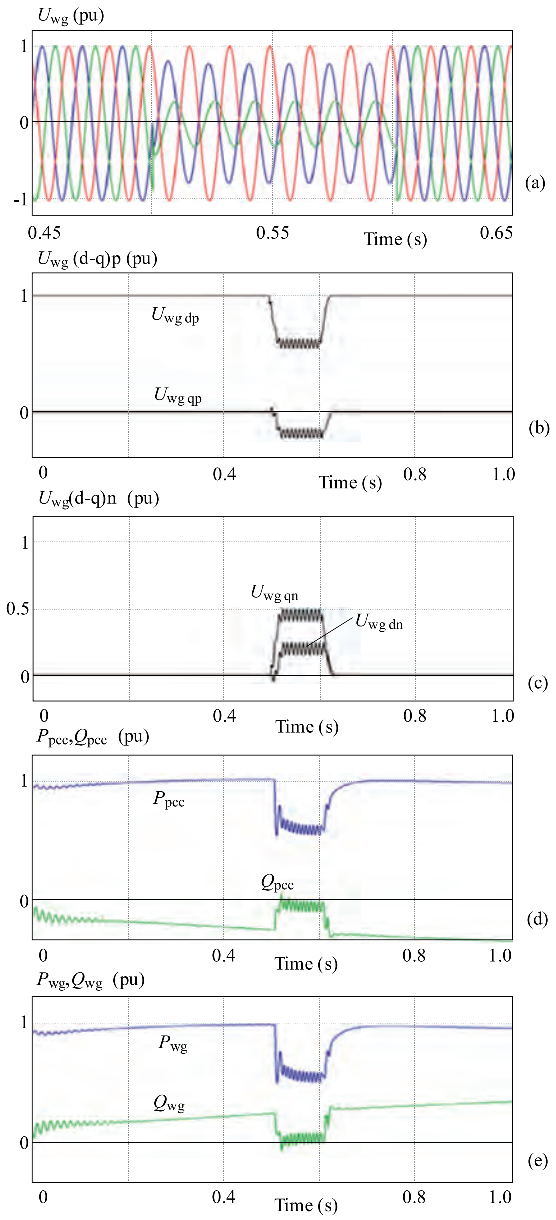


**Fig. 10.** The grid connected wind generator during phase-to-phase fault a – voltage dip b – positive sequence components c – negative sequence component d – active and reactive power at PCC e – active and reactive power at wind generator

## 6 CONCLUSION

The proposed DVR can recover voltage dip and provide real and reactive power support demanded by the induction generators. Hence fault ride through capability of the Induction generator based wind farm is improved with the aid of a DVR. The wind generator is able to remain connected to the grid without loss of stability and guarantee the reliability of the system. The proposed control scheme can also limit the fault current and protect the wind generator from destruction. Wind farm modelling and DVR control strategies are simulated using matlab which demonstrates the viability of the proposed scheme. The results show that the control technique is very effective and yield excellent compensation for voltage dip and associated problems.

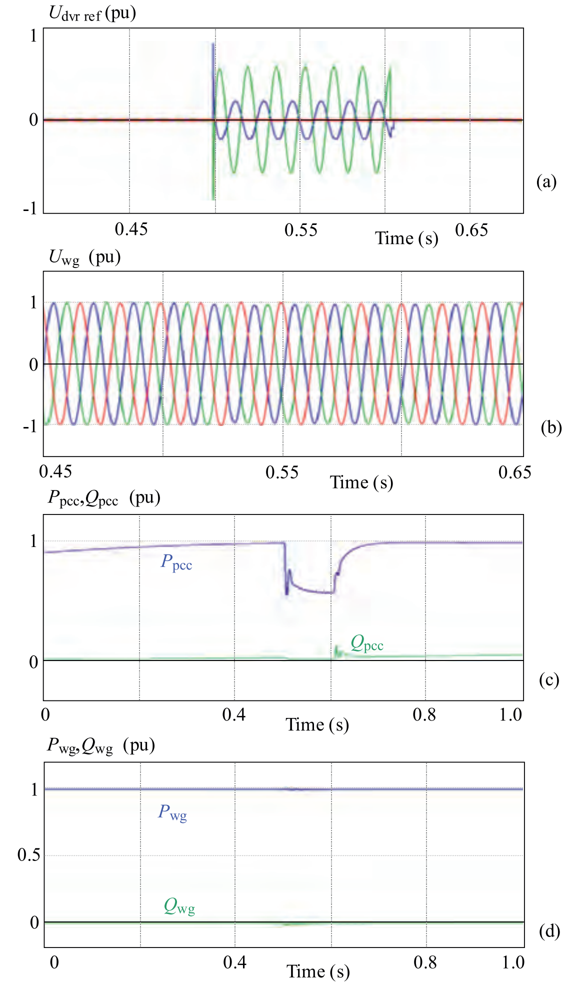


**Fig. 11.** The grid connected wind generator after phase-to-phase fault compensation a – DVR reference signal b – compensated voltage c – active and reactive power at PCC d – active and reactive power at wind generator

## Acronyms

| | |
|---|---|
| STATCOM | Static Compensator |
| SPLL | Software Phase Locked Loop |
| PD | Phase detector |
| PCC | Point of Common Coupling |
| SPWM | Sinusoidal Pulse width modulation |
| PI | Proportional-Integral |
| DVR | Dynamic Voltage Restorer |
| SVC | Static Var Compensator |
| $d$–$q$ | Rotating reference frame |
| $\alpha$–$\beta$ | Static reference frame |
| LF | Loop filter |
| SS | Sub Station |
| DVR | Dynamic Voltage Restorer |
| SVC | Static Var Compensator |

| | |
|---|---|
| $d$–$q$ | Rotating reference frame |

**Subscripts**

| | |
|---|---|
| $U_{abc}$ | Three phase voltage |
| $U_c$ | Compensation voltage |
| $U_{wg}$ | Wind generator voltage |
| $U_g$ | Grid voltage |
| $U_d$ | Direct axis voltage |
| $U_q$ | Quadrature axis voltage |
| $U_o$ | Zero sequence voltage |
| $U_M$ | Maximum voltage |
| $\phi_p$ | Phase difference |
| $\theta_d$ | Estimated angle |
| $n_{s1}$ | Synchronous speed |
| $n_m$ | Mechanical speed |
| $s_1$ | Fundamental slip |
| $s_{low}$ | Slip during voltage dip |
| $\omega_d$ | Angular velocity |
| $U_{rated}$ | Rated voltage |
| $U_{low}$ | Voltage dip |
| $\omega_{ff}$ | Nominal frequency |
| $U_\alpha$ | In-phase voltage |
| $U_\beta$ | Quadrature-phase voltage |
| $U_{gp}$ | Positive sequence voltage |
| $U_{gn}$ | Negative sequence voltage |
| $U_{DVR(d\text{–}q)}$ | DVR voltage in the $dq0$ frame |
| $U_{g(d\text{–}q)}$ | Grid voltage in the $dq0$ frame |
| $U_{wg(d\text{–}q)}$ | Wind generator voltage in the $dq0$ frame |
| $P_{gap}$ | Air gap power |
| $P_{loss\,rated}$ | Power loss at rated condition |
| $P_{loss\,low}$ | Power loss during voltage dip |

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