Assessment of control strategies for fault ride through of SCIG-based wind energy conversion systems

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ABSTRACT
With increasing penetration of wind energy into the power grid, researchers have started focusing more on control and coordination of wind energy conversion systems (WECS) with the other components at system level, especially during fault. It is important to implement a suitable fault ride through control strategy to avoid tripping of the generators when the power system is subjected to voltage dips normally below 90% of nominal voltage. The dips below 90% may lead to a significant loss of generation and frequency collapse, followed by a blackout. This article implements and assesses the methodologies to deal with such situations for squirrel cage induction generator-based wind energy conversion systems employing fully rated power electronic converters. Three distinct control techniques—namely, balanced positive sequence control, positive negative sequence control, and dual current control—have been simulated and applied to grid side converter of SCIG-based WECS. The performance of all the three control strategies has been compared and presented in this work. During this study, the system is subjected to the most common unsymmetrical line to ground (LG) fault and most severe symmetrical LLL fault on grid for the purpose of analysis.

1. Introduction
Due to the increasing demand of electrical energy and various environmental restrictions, the present trend emphasizes alternative sources of energy. Wind energy is an attractive alternative and is the largest used renewable energy source among all options available. In India, installed capacity of wind power was 22,465 MW out of total global installed capacity of 369,597 MW at the end of year 2014. More than 51 GW of new wind power capacity was brought online during 2014, which is a record. This growing capacity of wind energy demands more reliability from wind energy providers. In case of fault, the voltage of the grid drops (normally below 90% of nominal grid voltage). Under such circumstances, the wind energy conversion system (WECS) is expected to remain connected to the grid so that blackout is avoided. In such conditions, the fault ride through (FRT) capabilities of the WECS are of paramount importance. Many of the already operating wind turbine (WT) control systems are not equipped with the FRT feature. In order to make them acceptable according to new grid codes, these are to be upgraded, which may not be possible in an economical way.

Different strategies to improve FRT capabilities of converters have been presented by various authors. Many strategies using methodologies such as reachability theory and devices such as nine switch converters, lithium ion capacitors, dynamic voltage restorers, static VAR compensators, and static synchronous compensators (STATCOM) have been shown to improve FRT of WECS, but they increase the overall cost of the system especially in WECS with full rated converters. A nonlinear controller design has been presented for power converter-based WECS that is capable of maintaining current levels within its design limits, even at greatly reduced voltage level during fault.

The existing FRT control strategies consider only positive sequence currents, but during unsymmetrical fault, negative sequence components appear in the machine current. Therefore, appropriate control that considers the effects of negative sequence components should be adopted to overcome the negative impacts of unsymmetrical faults. In order to address this aspect, this article presents a comparison of three distinct strategies—namely, balanced positive sequence control (BPSC), positive negative sequence control (PNSC) and dual current control (DCC). The control strategies are applied on the grid side converter of squirrel cage induction generator (SCIG)-based WECS. The performance of each of these three control strategies is studied in coordination with usual controls of SCIG-based WECS such as de-loading control, MPPT, direct torque control, and vector control.

2. FRT control strategy for machine side converter
A squirrel cage induction generator of 2.2 kW, 415 V, 50 Hz rating has been used in this work. Two fully rated back-to-back connected voltage source converters—namely, generator or machine side converter (MSC) and grid side converter
positive and negative sequence quantities, respectively. Other
symbols such as $G$, $p$, $q$, $v$, and $i$ have their usual meanings as
conductance, real power, reactive power, voltage, and current,
respectively.

### 3.1. Balanced positive sequence control (BPSC)

In BPSC, for calculating current references, the positive
sequence component of the grid voltage is used as written:

$$i_p^+ = G^+ v^+ \text{ where } G^+ = \frac{p}{|v^+|^2}$$

Current vector of Eq. (1) consists of a set of perfectly balanced
positive-sequence sinusoidal waveforms. Under unbalanced
operating conditions, the instantaneous active power deliv-
ered to the grid changes and differs from $P$ mainly because of
the interaction between the positive-sequence injected current
and the negative-sequence grid voltage. Instantaneous power
to the grid can be given as

$$p = v.i_p^+ = v^+.i_p^+ + v^-i_p^- = P + \bar{p}$$

Similarly, instantaneous reactive power exchange with the
grid is

$$q = |v \times i_p^+| = |v^+.i_p^+| + |v^-i_p^-| = 0 + \bar{q}$$

where $x$ denotes the cross product, $P$ is the average power to
be injected to the grid, and $\bar{p}, \bar{q}$ are the double frequency
oscillations terms in real and reactive power, respectively.

### 3.2. Dual current control scheme

This control is accomplished by separating positive and nega-
tive sequence currents by using positive-negative sequence
detector. Two different controllers are used, one for control-
ling positive sequence currents and another for controlling
negative sequence currents. This positive and negative
sequence detection system also provides an effective solution
for grid synchronization of power converters during grid
faults. As per Ref., active and reactive powers ($P$ and $Q$)
for a system with unbalanced three-phase voltages can be
written as

$$P(t) = P_o + P_{\Delta 1} \cos(2\omega t) + P_{\Delta 2} \sin(2\omega t)$$
$$Q(t) = Q_o + Q_{\Delta 1} \cos(2\omega t) + Q_{\Delta 2} \sin(2\omega t)$$

where

$$P_o = 1.5 \left(E_{d}^{p}I_{d}^{p} + E_{q}^{p}I_{q}^{p} + E_{d}^{n}I_{d}^{n} + E_{q}^{n}I_{q}^{n}\right)$$
$$P_{\Delta 1} = 1.5 \left(E_{d}^{p}I_{d}^{p} + E_{q}^{p}I_{q}^{p} + E_{d}^{n}I_{d}^{n} + E_{q}^{n}I_{q}^{n}\right)$$
$$P_{\Delta 2} = 1.5 \left(E_{d}^{p}I_{d}^{p} - E_{q}^{p}I_{q}^{p} - E_{d}^{n}I_{d}^{n} + E_{q}^{n}I_{q}^{n}\right)$$
$$Q_o = 1.5 \left(E_{d}^{p}I_{d}^{p} - E_{d}^{n}I_{d}^{n} + E_{q}^{n}I_{q}^{n} - E_{q}^{n}I_{q}^{n}\right)$$
$$Q_{\Delta 1} = 1.5 \left(E_{d}^{p}I_{d}^{p} - E_{q}^{p}I_{q}^{p} - E_{d}^{n}I_{d}^{n} + E_{q}^{n}I_{q}^{n}\right)$$
$$Q_{\Delta 2} = 1.5 \left(E_{d}^{p}I_{d}^{p} + E_{q}^{p}I_{q}^{p} - E_{d}^{n}I_{d}^{n} - E_{q}^{n}I_{q}^{n}\right)$$

Here the voltages and currents are expressed in positive
(superscript "p") and negative (superscript "n") synchronous
components.
reference frame (SRFs). Neglecting higher order terms (Qc2 and Qs2) of reactive power, the power coefficients written in matrix form are

$$\begin{bmatrix} \frac{2}{3} P_o \\ \frac{1}{3} P_o \end{bmatrix} = \begin{bmatrix} E^d_p E^d_q E^q_d E^q_p E^n_d E^n_q \\ E^n_p - E^d_q E^d_p - E^n_q E^q_p E^n_d E^n_q \end{bmatrix} \begin{bmatrix} i^p_d(t) \\ i^q_d(t) \end{bmatrix}$$  \tag{6}

The high-order coefficients Pc2, Ps2, Qc2, and Qs2 are caused by voltage imbalance. The dc voltage level at the dc-link is determined by the real power (P) delivered through dc-link. If P varies with time for Pc2, Ps2 not being equal to zero, then the dc-link voltage fluctuates, and a 100 Hz ripple appears in it. In this work, coefficients Pc2, Ps2 are nullified to keep the dc level constant, while Qc2 and Qs2 are not considered.

### 3.3. Positive negative sequence control (PNSC)

Active power P can be delivered to the grid by injecting sinusoidal positive- and negative-sequence currents at the PCC. To achieve this, the following constraints should be imposed in the current reference calculation:

$$v^+ i^+_p + v^- i^-_p = P$$  \tag{7}
$$v^+ i^+_p + v^- i^-_p = 0$$  \tag{8}

From Eq. (7) and Eq. (8) negative and positive sequence reference current can be written as

$$i^-_p = -g^- v^- \text{ where } g^- = \frac{v^+ i^+}{|v^+|^2}$$  \tag{9}
$$i^+ p = g^+ v^+ \text{ where } g^+ = \frac{v^+ i^+}{|v^+|^2 - |v^-|^2}$$  \tag{10}

Adding Eq. (9) and Eq. (10), the final current reference becomes

$$i^m_p = i^+ p + i^- p = g^m (v^+ - v^-)$$  \tag{11}

Equation (11) indicates that the injected current and voltage vectors have different directions. Consequently, the instantaneous reactive power delivered to the grid is not equal to zero but exhibits second-order oscillations and is given by

$$q = |v \times i^m_p| = v_L i_q$$  \tag{13}

In Eq. (13), vL is an imaginary 90° leaded version of the voltage vector v, which can be given as

$$v_{abc} = [T_L] v_{abc}; [T_L] = \frac{1}{\sqrt{3}} \begin{bmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{bmatrix}$$  \tag{14}

This section provides current injection strategies for the controls discussed in previous section.

### 4. Current injection strategies

In earlier control strategies, active current reference and voltage vectors with the same sequence and frequency had always the same direction. Therefore, the instantaneous reactive power injected in the grid by means of such strategies was entirely oscillatory having mean value equal to zero over a grid cycle. The reactive current vector $i_q$ is obtained. This is in-quadrature with the voltage vector v and injects the following instantaneous reactive power to the grid:

$$q = |v \times i_q| = v_L i_q$$  \tag{13}

In Eq. (13), vL is an imaginary 90° leaded version of the voltage vector v, which can be given as

$$v_{abc} = [T_L] v_{abc}; [T_L] = \frac{1}{\sqrt{3}} \begin{bmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{bmatrix}$$  \tag{14}

This section provides current injection strategies for the controls discussed in previous section.

#### 4.1. Current references for balanced positive sequence control

The active and reactive current references for delivery of powers P and Q to the grid are calculated as

$$i^p_p = \frac{P}{|v|^2} v^+$$  \tag{15}
$$i^q_q = \frac{Q}{|v|^2} v^+$$  \tag{16}

assuming that the current injected by inverter perfectly tracks the power references P and Q because of the interaction between the injected current and the negative-sequence grid voltage.

$$p = v \cdot i^m_p = v^+ \cdot i^+ p + v^- \cdot (i^+ p + i^- q) = p + \tilde{p}$$  \tag{17}
$$q = v_L \cdot i^m_q = v^+ \cdot i^+ q + v^- \cdot (i^+ q + i^- q) = Q + \tilde{q}$$  \tag{18}

In this case, an unbalanced voltage guarantees the appearance of $\tilde{p}$ and $\tilde{q}$ for any not-null value of P and Q. On the other hand, the resulting currents with this algorithm are sinusoidal, and hence their amplitudes are easy to predict.

#### 4.2. Current references for dual current control

Nullifying Pc2 and Ps2 in Eq. (6), we obtain the reference currents in dq-frame as

$$\begin{bmatrix} I^p_d(t) \\ I^p_q(t) \\ I^q_d(t) \\ I^q_q(t) \end{bmatrix} = \begin{bmatrix} E^d_p E^d_q E^q_d E^q_p E^n_d E^n_q \\ E^n_p - E^d_q E^d_p - E^n_q E^q_p E^n_d E^n_q \end{bmatrix}^{-1} \begin{bmatrix} 2 P_o \\ \frac{2}{3} Q_o \end{bmatrix}$$  \tag{19}

With a current choice as Eq. (19), the coefficients Pp2 and Ps2 vanish, while reactive power high-order coefficients Qp2 and Qs2 remain. This implies that an alternating reactive power exists, although the average reactive power is equal to Qo. However, the limited degrees of freedom prevented any other way of nullifying all coefficients. Zero reactive power exchange can be achieved by making Qo equal to zero and derive current references.
4.3. Current references for positive negative sequence control

Assuming that the currents are unbalanced but not distorted,

\[ p = v \cdot i = v^+ \cdot i^+ + v^- \cdot i^- + v^+ \cdot i^- + v^- \cdot i^+ \] (20)
\[ q = v_L \cdot i = v_L^+ \cdot i^+ + v_L^- \cdot i^- + v_L^+ \cdot i^- + v_L^- \cdot i^+ \] (21)

The active and reactive current references can be calculated by imposing the following constraints on Eq. (20) and Eq. (21):

\[ v^+ \cdot i_p^+ + v^- \cdot i_p^- = P; v^+ \cdot i_q^+ + v^- \cdot i_q^- = 0 \] (22)
\[ v_L^+ \cdot i_q^+ + v_L^- \cdot i_q^- = Q; v_L^+ \cdot i_p^- + v_L^- \cdot i_p^+ = 0 \] (23)

Active and reactive reference currents are given by

\[ i_p^+ = \frac{P}{|v^+|^2 - |v^-|^2} (v^+ - v^-) \] (24)
\[ i_q^+ = \frac{Q}{|v^+|^2 - |v^-|^2} (v_L^+ - v_L^-) \] (25)

If the currents shown in Eq. (24) and Eq. (25) were injected into the unbalanced grid, the instantaneous powers \( p \) and \( q \) would differ from the power references because of the interaction between voltage and current vectors with different sequence and direction, that is,

\[ p = v \cdot \left( i_p^+ + i_q^+ \right) = v^+ \cdot i_p^+ + v^- \cdot i_p^- + v^+ \cdot i_q^- + v^- \cdot i_q^+ \] (26)
\[ q = v_L \cdot \left( i_p^+ + i_q^+ \right) = v_L^+ \cdot i_q^+ + v_L^- \cdot i_q^- + v_L^+ \cdot i_p^- + v_L^- \cdot i_p^+ \] (27)

Therefore, the amplitude of the oscillations in \( p \) and \( q \) will depend on the values of \( P \) and \( Q \). Then a delivery of full active power will produce a constant value of \( p \), while the \( q \) component will have an oscillatory term. This relationship is swapped if just \( Q \) is delivered to the grid.

5. Simulation of control strategies

Three distinct control strategies—namely, balanced positive sequence control, dual current control, and positive negative sequence control—have been simulated on the basis of the explanations given in sections 3 and 4 of this article. These strategies have been applied to grid side converter of SCIG-based variable speed grid connected WECS. All these strategies have been simulated in a Matlab/Simulink environment and are presented in this section.

5.1. Simulink model of balanced positive sequence control

A Simulink model of balanced positive sequence control strategy used during this study is given in Figure 3. As reflected in the figure, only positive sequence component of grid voltage is detected, which is used for generating current references in this control strategy.

5.2. Simulink model of dual current control

Figure 4 shows the Simulink model of a dual current controller used for grid side converter in SCIG-based WECS. Two current controllers are used for positive and negative sequence separately in this strategy. Positive sequence is controlled in positive SRF, while the negative sequence is controlled in negative SRF.

5.3. Simulink model of positive negative sequence control

A Simulink model of a positive negative sequence controller used for grid side converter is illustrated in Figure 5. In this model, positive and negative phase detection is done by using second order generalized integrator (SOGI). An additional imaginary perpendicular voltage

![Figure 3. Simulink model of BPSC strategy.](image-url)
6. Simulation results and discussion

This section discusses the results of the simulation of WECS with and without the fault ride through control. Two types of fault conditions—namely, line to ground (LG) and three-phase fault (LLL)—are simulated, and the results are analyzed. These two fault conditions are particularly selected to study the impacts of most commonly occurring unsymmetrical (LG) fault and the most severe symmetrical (LLL) fault. The proceeding figures present the results achieved by applying three distinct control strategies. These results are analyzed in detail. Figures 6 and 7 illustrate the behavior of SCIG-based WECS during unsymmetrical and symmetrical faults, respectively, without application of any FRT. The fault was applied at 1.5 seconds, which continued for 0.5 seconds (25 cycles). Figures 8 to 13 show the behavior of WECS during LG and LLL faults with application of FRT control abilities applied. During this part of study, fault was applied at 1.5 seconds for 1 second (50 cycles).

6.1. Simulation results without fault ride through control

Figures 6 and 7 show the simulation results without FRT control for LG and LLL faults, respectively. In each case, a dip in voltage of around 90% is observed while rise is noticed in converter current. Huge oscillations of twice the fundamental frequency (100 Hz) are observed in real and reactive power during LG fault. The real power fluctuations are reflected as double frequency ripples in dc-link voltage. In case of LLL fault, the grid is not able to receive any power at all; therefore, there is a shoot-up of capacitor (dc-link) voltage, which may damage the capacitor. The above results present the problems at the time of a grid fault without any FRT control algorithm.

6.2. Simulation results with balanced positive sequence control

Figures 8 and 9 show the simulation results of WECS with BPSC implemented on its grid side converter for LG and LLL faults, respectively. The de-loading of the generator side converter has been done to limit the dc-link voltage at its threshold, which is set at 120% of V_{dc} considering a factor of safety of 20%. The currents are sinusoidal, and their peaks are limited to 10A by current-
limiting control. Reactive power is injected into the grid for faster voltage recovery. The pitch control mechanism has been enabled to restrict the generator speed within limits. Huge oscillations in real and reactive power at twice the fundamental frequency are observed due to the interaction of negative sequence voltage with positive sequence currents in case of an unbalanced fault. Real power oscillations are producing ripples in dc-link voltage. On application of de-loading on generator side converter for limiting dc-link voltage, a reduction in generator current is also observed.

6.3. Simulation results with dual current control

Figures 10 and 11 show the simulation results of WECS with DCC applied on its grid side converter for LG and LLL faults. A reactive power injection into the grid is observed during both types of fault. This reactive power supports the grid voltage during fault. The real power oscillations are completely eliminated in any fault situation, but there are reactive power oscillations during unbalanced fault. Further, the elimination of real power oscillations has resulted in elimination of ripple from dc-link voltage. The total converter volt-ampere has been limited to the nominal value during both types of fault, which limit the converter currents to a safe value. The dc-link voltage is limited below its maximum value, which indicates that de-loading of the generator side converter is working satisfactorily. The currents are sinusoidal but unbalanced in the case of an unsymmetrical fault, and hence it is clear that a control of negative sequence currents is also performed.
6.4. Simulation results for positive negative sequence control

Figures 12 and 13 show the simulation results of WECS using PNSC on its grid side converter for LG and LLL faults. The de-loading of the generator converter is able to limit the dc-link voltage at 120% of $V_{dc}$ considering a factor of safety of 20%. Reactive power is injected into the grid for faster voltage recovery. The pitch control mechanism has been enabled to limit the generator speed within limits. Huge oscillations in real and reactive power at twice the fundamental frequency are observed due to the interaction of negative sequence voltage with positive sequence currents in case of an unbalanced fault. Real power oscillations are reflected as ripple in dc-link voltage. A reduction in generator current due to de-loading is also observed.

7. Conclusions

A detailed comparison of different aspects of three distinct grid fault ride through strategies has been presented in this article. The system has been simulated and run under unsymmetrical and symmetrical grid fault conditions without
application of any FRT control to study the problems arising and behavior of SCIG based WECS during fault. Complete coordinated control for FRT of SCIG-based WECS using three distinct state of the art controllers for grid converter has been developed, simulated, and compared for analysis purpose. A de-loading control of generator side converter has successfully limited the dc-link voltage at threshold value during fault. A reactive power injection for better grid support during fault has been incorporated in simulations. All the control techniques work well under symmetrical fault conditions showing well-coordinated control and effectiveness of generator side controller and grid side controller. It has been observed that, in case of unsymmetrical fault, the active and reactive power oscillations exist in case of BPSC and PNSC control, while DCC prevents oscillations in active power. The oscillations in reactive power, in case of DCC, may also be removed by nullifying the higher-order reactive power coefficients \( Q_{s2} \) and \( Q_{c2} \) that can be done by including these coefficients in equation 6 that have been struck out in this study. The inclusion of these coefficients will lead to design of even more complicated control algorithms. As per the above discussion, dual current control strategy seems to be a promising option even for the unsymmetrical fault conditions.
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Figure 12. Simulation results for LG fault with positive negative sequence control.

Figure 13. Simulation results for LLL fault with positive negative sequence control.
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