Rating Requirements of the UPQC to Integrate the FSIG Type Wind Generation to the Grid

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Rating Requirements of the UPQC to integrate the FSIG Type Wind Generation to the Grid

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Abstract: The ability of wind generation to remain connected to the grid in the event of system faults and dynamic reactive power compensation are two aspects of grid integration, which have received particular attention. The wind driven, Fixed Speed Induction Generator (FSIG) on its own fails to fulfil these requirements of grid integration. This paper investigates the application of a Unified Power Quality Conditioner (UPQC) to overcome the grid integration problems of the FSIG. The role of the UPQC in enhancing the fault ride through capability of the generator is investigated under both full and partial terminal voltage restoration. A realistic estimation of the rating requirements of UPQC for this type of application is carried out. A general principle is presented to choose the most practical and economical rating of the UPQC. The performance comparison of a UPQC and a STATCOM to aid fault ride through of a 2 MW FSIG under Irish Grid Code requirements has been carried out and the UPQC is found to be more economical in relation to device rating.

Keywords : Wind Generation, Fixed Speed Induction Generator, Fault Ride Through, Unified Power Quality Conditioner

1 Introduction

The increased level of wind penetration into the power system has resulted in revision of Grid Codes for wind generators by the Transmission System Operator (TSO) in the Republic of Ireland [1]. Among various wind generators, the conventional Fixed Speed Induction Generator (FSIG) fails to fulfil some of the important grid integration requirements such as reactive power compensation, terminal voltage control and fault ride through. Generally an external active or a passive compensating device is used with the FSIG to tackle these problems. In this paper, the application of a Unified Power Quality Conditioner (UPQC) for achieving a grid code compliant FSIG is investigated. The UPQC is a power conditioning device, which is a combination of a shunt (SHUC) and a series (SERC) compensators. It stands as a solution to almost any power quality problem because of its structure [2, 3]. The SERC regulates the voltage quality at the Point of Common Coupling (PCC) and the SHUC is responsible for current compensation at the PCC. A simulation based analysis has been carried out to investigate the suitability of application of the UPQC to the FSIG based wind generator. A realistic estimation of the rating of the UPQC required for this type of application has been investigated. A general principle has been presented to decide on the optimum rating of the individual compensators of the UPQC, which helps in economical installation of the same. The performance comparison of the UPQC and the STATCOM under VAR control mode are carried out for similar network and fault condition on a 2 MW wind turbine.

The paper contains seven sections. Key points of Irish Grid Code for wind is presented in second section. The third section deals with the brief explanation of the voltage ride through problem faced by the FSIG and the fourth section describes the solution developed for the same. In the fifth section, a detailed explanation of the simulation model is provided. The sixth section deals with the results and the discussion and conclusions on the work are provided in the seventh section.

2 Irish grid code requirements for wind generators

In the Republic of Ireland, the Transmission System Operator (TSO) released a new Grid Code in relation to wind energy in July 2004. The key points of Irish grid code for wind are listed here [1]:

- The generator must stay connected to the grid when a voltage sag profile shown in Fig. 1. is experienced at the high voltage terminals of the grid connection transformer (definition of the voltage sag considered in the paper is in accordance with the IEEE Std. 1159-1995, voltage sag level corresponds to the voltage remaining at the terminals where the voltage sag is specified, for instance, 45% sag corresponds to 45% remaining voltage).
- During the voltage sag, the generator must provide the active power to the grid at least proportional to the retained voltage and maximise the reactive current at least until 600ms or until clearance of the voltage sag.
- Within 1 second of clearance of the sag, a wind generator must provide at least 90% of the available real power.
- The power factor, reactive power generation/consumption and terminal voltage at the wind generator connection point must be regulated.
- The wind generator must continue to work normally under a slight frequency variation (49.5Hz to 50.5Hz).

3 Analysis of voltage ride through

The FSIG is an established technology in the field of wind generation. 23% of the wind generators operating worldwide are of FSIG type [4]. However, the provision of reactive power compensation and ensuring the fault ride through capability for this type of generator is a challenging task. Whenever a fault occurs in the power system, a voltage sag of varying severity is experienced at the machine terminals. This is accompanied by a significant reactive power requirement from the connecting power system. As the FSIG is a reactive power sink, it needs an external device to fulfil its reactive power requirement even during normal operating conditions. The mismatch in the electrical and mechanical torque during the sag period causes over-speeding of the machine. The limit of stability of the machine is reached once the slip approaches its pull-out value. In this situation, the generator fails to build its terminal voltage and it will be tripped by the under-voltage or over-speed relays [5, 6].

4 The proposed solution to enhance grid integration

The application of active filters to provide the reactive power compensation and additional fault ride through capability to generators in the field of wind generation is gaining popularity. Typically, this is done by mechanically switched capacitors connected at the machine terminals [7]. This method suffers from a few drawbacks. The ability of a capacitor to provide reactive power support declines when there is a voltage sag condition at its terminals due to a power system fault. The mechanical switching reduces the life span of the scheme. Also the gearbox experiences excessive stress due to step voltage changes [7]. The performance of a Static VAR Compensator (SVC) based reactive power compensation is better than a fixed capacitor, but is limited by its rating and must be sized appropriately if it is to address transient events adequately. In addition, since SVC's are capacitor based, the ability to supply reactive power declines by the square of the voltage, which can reduce the ability of a SVC to provide benefit in the case of severe voltage sags. The application of a Static Synchronous Compensator (STATCOM) for wind generation is discussed in [8,9,10,11]. The rating of the STATCOM device is based on the available mechanically switched capacitor at the terminal of the FSIG, the strength of the transmission network, the generator rating and the time limit of the minimum voltage requirement at the high voltage terminal of the connection transformer as set by different Grid Codes. In [8,9] the Grid Code of Great Britain is considered in which the generator has to remain connected to the power system for at least 140 ms when the voltage on the high voltage side of the transmission system is zero. [10,11] are based on the Spanish Grid Code, where the generator has to remain connected to the power system at least until 500ms after the occurrence of a fault during which the PCC voltage is 20% of the nominal value. Based on the above mentioned criteria, STATCOM ratings in previous work range from 0.3 pu to 1 pu. In [11] the transient overload capacity of STATCOM is 1.1 pu for 1 sec. But the STATCOM is aided with Mechanically Switched Capacitors (MSC). The longer the period of the grid code requirement for low voltage operation, the higher will be the increase in the machine speed and the higher will be the reactive power required to establish pre-fault operating conditions after the fault clearance. This calls for higher rating of power electronic equipments such as STATCOM when applied to aid fault ride through capability. Also, the STATCOM rating designed for some particular grid codes pose an upper limit of critical clearance time of fault beyond which the device fails to help FSIG to achieve fault ride through. For instance in [8], for the system considered, the application of a 1pu STATCOM allows the critical clearance time of fault to be 225 ms. In [9] application of a 1pu STATCOM with battery energy storage and breaker resistor allows 621 ms of critical clearance time. It is to be noted that the performance of wind generators during grid voltage sag will be dependent on network parameters (primarily short circuit level). That will influence the connected STATCOM rating. The published literature used grid codes of different countries and various network parameters which are not identical to each other. Hence a common code and standard network is not available. For the present paper, Irish grid code and typical transmission network parameters are considered.

The fault ride through voltage profile imposed by the Irish grid is given in Fig. 1. The duration, for which the generation must stay connected during any fault, which has resulted in 15% of the nominal voltage at the HV side of grid connected transformer, is 625 ms. In the present paper it has been shown that to comply with the Irish grid code, instead of connecting a STATCOM of higher rating, if the voltage control and reactive power control are shared by the two compensators of a UPQC, (one in series and one in shunt) the performance of the overall system will be superior. The advantages of connecting a UPQC instead of a STATCOM are indefinitely long critical clearance time of the fault and 100% real power transfer even under fault condition when sag experienced is low. (Full power transfer up to 55% voltage sag is designed in this paper).

The UPQC is a combination of a shunt (SHUC) and a series (SERC) active filter, cascaded via a common DC link capacitor. Each compensator is an IGBT based full bridge inverter, which may be operated in a voltage or current controlled mode depending on the control scheme. The structure of this device makes it very versatile and makes it more flexible than any single inverter based device [12-16]. The UPQC finds its application in mitigating various power quality problems. In the proposed solution the UPQC is connected at the Point of Common Coupling of the FSIG. The capital cost involved in the installation of this device is higher than any other FACTS based solution because of its twin inverter structure. In this paper a cost effective method of choosing the inverter VA rating without compromising on the overall performance of the device is proposed.

5 Simulation study and analysis

A simulation-based analysis is carried out on the system shown in Fig. 2.The behavior of the system in the presence of a UPQC and a STATCOM are simulated. When the switch SW1 is open, the UPQC model is active. The closure of switch SW1 puts series compensator (SERC) of the UPQC in idle condition and only the shunt compensator (SHUC), which is similar to a STATCOM in VAR control mode is active. A switched resistive bank (R_{BR}) is employed to divert the real power during severe voltage sags. The system is modelled in MATLAB/Simulink. As mentioned in [17] “if the high order harmonics generated by voltage-sourced converters is not important, these devices can be replaced by simple voltage sources producing the same average voltage over one cycle of the switching frequency”. Therefore, a dynamic phasor simulation method has been deemed appropriate for system modelling.

5.1 The Network and the machine model

The network and the machine model are built with the standard blocks available in the SimPowerSystem toolbox of MATLAB/Simulink. The asynchronous machine block is considered, which can run both as a motor and a generator based on the convention of the mechanical torque. The capacity of the wind turbine is considered to be 2 MW. The parameters of the machine are provided in Appendix I [9]. The Power Factor Capacitor (PFC) provides 50% of the reactive power required by the generator at 100% power output. A double line network is considered here with a X/R ratio of 10. X and R values are typically chosen such that the short circuit capacity at machine terminals is 20 MVA. Clearly the fault level at the PCC will have significant effect on the ability of the generator to ride through the fault. The lower the fault level, the less likely will be the ability of the generator to ride through. However, rather than investigating the effect of the fault level on the ride through capability, a specific level of voltage sag is used to characterize the severity of the fault. This is done so that the investigation can be compared with the typical requirement of the grid code. Moving the fault point F on one of the transmission lines simulates balanced faults of varying severity at PCC bus

5.2 The UPQC model

5.2.1 SHUC/STATCOM model

The SHUC/ STATCOM is controlled to maintain unity power factor at the PCC and DC link voltage at a constant value. The converter is modelled as a current controlled voltage source like in [18,19]. The measured values of different currents and voltages are converted to direct and quadrature axis components taking PCC bus voltage as reference. The direct current component (I_{SHUCd}) of SHUC/STATCOM is controlled to maintain DC link voltage at a constant value. The quadrature current component (I_{SHUCq}) is responsible for reactive power control at PCC. The PI block in DC link controller provides necessary direct reference current based on the difference in measured and set value of DC link voltage. The measured source current *Is* is converted to direct and quadrature component in *abc* to *dq* block of the control. To maintain unity power factor at PCC, Q_{PCCREF} and hence the quadrature component of source current I_{Sq} has to be zero. The PI block in the reactive power controller generates necessary quadrature current reference based on measured I_{Sq} component, which in ideal condition must be zero. The PI controllers applied in SHUC/STATCOM current controller generates necessary voltage at shunt converter terminals based on reference and measured shunt currents. The SHUC control blocks are presented in Fig. 3a.

5.2.2 SERC model

The SERC is controlled to maintain the bus voltage at a predetermined value (M bus voltage in Fig. 2) which is similar to a Dynamic Voltage Restorer (DVR). A feed-forward control is applied to achieve this. The positive sequence component is utilized to generate the balanced three phase reference. The PCC voltage is compared to the reference value. Any deviation of the PCC voltage from the reference value will result in appropriate voltage injection by the SERC to maintain M bus voltage at the reference value. The SERC control is shown in Fig. 3b.

5.2.3 DC Link model

The overall power balance of the UPQC is maintained through the DC link capacitor. When a voltage sag is addressed by the SERC, the real power proportional to the voltage injected is absorbed by the DC link. The DC link voltage controller of the SHUC/STATCOM in case of UPQC mode of operation ensures that this power is injected back into the power system thereby maintaining a constant DC link voltage. Therefore, overall real power absorbed or injected by the UPQC is null. In case of STATCOM mode of operation, only reactive power transfer has to be achieved through the shunt converter other than the real component of current drawn to maintain the DC link voltage at a constant value. The DC link model is designed on the basis of AC power balance [18,19] is shown in Fig. 3c.

During severe voltage dips causing low voltage sags real power exchanged between the UPQC and the network will be extremely high. This will result in a very high rating of the converters. In order to limit the rating of converters, switched resistor bank (R_{BR}) is applied to divert the real power if the voltage retained at the PCC is lower than 55% (This is further discussed in Section 6.4). The real power proportional to the remaining voltage at the PCC is only supplied to the grid if the voltage is lower than 55%.

The fundamental frequency representation of the UPQC can be seen in Fig. 4. The generator side voltage is represented as V_M. I_M is the generator current. V_{PCC} is the intermediate bus voltage and V_{inj} is the voltage injected by the SERC of the UPQC. The voltage is injected in phase with the positive sequence of the generator side voltage in the case study considered here. The generator side voltage is in phase with the PCC voltage. I_S is the grid current which is in anti-phase with the generator side voltage. I_C is the current injected from the SHUC of the UPQC. I_{BR} is the current through the breaker resistor whenever it is switched on and will be in phase with generator terminal voltage. Vector diagrams with V_{PCC} as reference for the normal operating condition and voltage sag condition are represented in Fig. 5a and Fig. 5b. Under normal operating conditions when the SHUC acts as a reactive power source, current I_C is injected by the SHUC. During a voltage sag condition, the active power absorbed by the SERC is injected to the network by the SHUC by injecting additional current I_S^1. If the I_{BR} component is present, it will reduce the real power component of the I_M, which flows through the SERC. The VA rating of the UPQC is a combination of the VA rating of the individual compensators. The rating of the SHUC is determined by the maximum current handled by the SHUC I_C, and the converter voltage V_{SHUC}. The rating of the SERC is determined by the grid current I_M, (that flows through it) and the injected voltage V_{inj}.

5.2.4 Breaking resistor model

The breaking resistors are connected at the point of connection of UPQC (at generator side) to divert the real power during voltage sags. They are modelled with resistor blocks available in the SimPowerSystem tool box and controllable switches. Its connection and disconnection from the network is controlled by the voltage sag measurement for a UPQC case and terminal voltage (M Bus) measurement for a STATCOM case. The power diverted by the resistive circuit should be directly proportional to the deficit voltage, to deliver the real power proportional to voltage retained at the grid. For the 2 MW generator case considered here 5 resistors (350 O each) are connected in parallel. They are switched in group appropriately based on the measurement of the sag level (i.e. injected voltage for a UPQC), and measurement of the terminal voltage for a STATCOM as shown in Fig.6 as category I, II and III. Similar approach has been shown in [9] in relation to a STATCOM application.

6 Simulation Results

The application of the UPQC is investigated by simulation-based analysis of different practical cases. The results are discussed in first four sections. The performance of a STATCOM applied to the system shown in Fig. 2 in VAR control mode is presented in the fifth sub-section.

6.1 Application of the UPQC

In the first set of studies, the model presented in Fig. 2 is considered without connecting the UPQC. The generator is delivering nominal power to the grid since mechanical torque is held constant at 1pu. A three phase balanced fault occurs at 10 sec and lasts for 500 ms. A voltage sag to15% is created at the PCC as a result of the fault. The PCC voltage and the speed are shown in Fig. 7. The fact that the machine becomes unstable and cannot ride through the fault can be seen here. The machine fails to build its terminal voltage even after the fault is cleared. The electrical torque of the generator reduces in this scenario. As the mechanical torque remains constant, the generator accelerates. As a result of this, the generator is required to be disconnected from the rest of the power system. Fig. 7 also shows the flow of active and reactive power PCC. The active power flow is greatly reduced and the generator draws a significant reactive power from the grid.

The simulation was repeated with the UPQC connected at the PCC at 5 sec. Fig. 8 shows the reactive power support supplied by the SHUC. The VAR drawn by the generator and the associated inductive devices from the grid drops to zero, after UPQC takes action. A three phase balanced fault is created at 10 second, which lasts for 625 ms. As a result of the fault a voltage sag to15% is created at the PCC. The time span of the fault is as per the requirement of the Irish grid code for wind generators. Figures 9a,b,c show the response of the UPQC and the generator. The voltage sag is sensed by the SERC and the deficit voltage is injected in phase with the PCC voltage. Thus, the generator does not experience the voltage sag and the over-speeding of the generator is avoided. The magnitude of the injected voltage (SERC voltage), PCC voltage and M bus voltage, generator speed and power flow at PCC can be observed in Fig. 9a. The real power proportional to the PCC voltage (0.15 pu) is supplied to the grid (according to Irish Grid Code) during the fault condition. 85% of the real power is diverted through the breaking resistor (9b). The variation of electromagnetic torque during and after the clearance of the fault can be seen in Fig. 9b.The power output of the generator, power at the PCC and the power diverted by the breaker resistors can be compared in Fig. 9b. The corresponding current flow at different parts of the circuit can be seen in Fig. 9c. The reactive power demand of the generator remains the same as the pre-fault value. The role of the UPQC in ensuring fault ride through of the generator can be well appreciated in this case study.

6.2 Performance under an unbalanced fault

A Line to Ground (L-G) fault is created at phase A in the midpoint of one of the transmission lines. The resulting voltage magnitude at the PCC can be seen in first plot of Fig. 10a. Corresponding injected and terminal voltages (M bus) can be also seen in second and third plots respectively. The terminal voltage is balanced and maintained at its desired level with the help of UPQC. Therefore, the generator continues to work in the same fashion. The variation in the speed, real and reactive power at the PCC can be seen in Fig. 10b.

6.3 Rating requirements of the UPQC

The rating of the UPQC to be installed in a particular wind generation site has to be decided by considering the generator rating, the sag level and the duration of the fault to be addressed by the SERC of the UPQC. In the case study considered here, UPQC is rated such that a 2 MW FSIG complies with Irish grid code. During a voltage sag, the terminal voltage of the generator need not be compensated to 100% to achieve fault ride through. But it is necessary to maintain it at a level so that the mismatch in the mechanical and electrical torque is such that the pull-out value of the slip is not reached. Several case studies were carried out to investigate this issue. A typical result is presented in Fig. 11, with a limit placed on the capacity of the SERC such that the terminal voltage of the generator is compensated up to 70 % of the nominal value during a three phase fault, which has resulted in a voltage sag to 15 % at the PCC (0.55 pu compensation from SERC). The over-speeding of the generator is avoided in spite of reduced terminal voltage operation. The real and reactive power flow at the PCC can be observed in Fig. 10. 15% of the real power is supplied to the grid, according to the grid code requirement.

The generator achieves the fault ride through and returns to normal operation after the clearance of the fault within 1 sec. This implies that the rating of the individual compensators of the UPQC can be limited in order to minimise the overall rating of the UPQC, without compromising on the desired objective.

6.4 Optimising the rating of the UPQC

There is obviously a dependency between the rating of the SERC and the SHUC. Though the reduction in the injected voltage reduces the rating of the SERC, it increases the rating of the SHUC. This can be explained with the result shown in the Fig. 12. The real power flow through the SHUC during 0.85pu and 0.55pu compensation levels are both the same (real power output at the PCC must be held constant at 15% of 2MW). Reactive power output of the SHUC increases with the 0.55pu compensation from SERC. The increase in generator speed is negligible during 0.85pu compensation whereas there is a 1.5% increase in the speed under 0.55pu compensation. The increased slip increases the reactive power demand of the generator when the fault is cleared. This increases the VA rating of the SHUC which is operating in VAR control mode. A typical VA rating curve of the UPQC to 15% voltage sag is shown in Fig. 13. It is a plot of VA rating of the UPQC versus SERC voltage compensation provided. The plot represents the operating region of UPQC, where fault ride through is achieved by the generator.

Up to 0.55pu compensation, the reduction in the SERC rating is more significant than the increase in the SHUC rating. Beyond this point of compensation, the post-fault reactive power demand becomes higher and increase in the SHUC rating dominates. Reduced terminal voltage operation is the reason for higher post-fault VAR demand. Therefore 0.55pu compensation point (with a UPQC rating of 1.47 pu,) is considered to be the minimum practical rating for a UPQC required for the particular FSIG under consideration in order to comply with the Irish grid code. The reduction in the overall rating of the UPQC from 100% voltage compensation to 70% voltage compensation is 10% (i.e. 290 KVA).

When the PCC voltage is 55% and above, a UPQC of rating 1.47pu is applied at the PCC can be operated to transfer full power (2MW) rather than the real power proportional to retained PCC voltage. The resistor bank does not have to be switched on in these cases because the rating of the UPQC is sufficient to transfer the full power. This full power transfer is an added advantage of the UPQC application compared to other FACTS devices. Fig. 14 shows the typical results for a 55% sag. A three phase fault created at 10 sec results in a 55% voltage sag at the PCC. The fault is cleared at 12.2 sec (the Irish grid code time limit at 55% sag is 1.9 sec) . The generator speed returns to pre-fault value after a short period of transients. The real and reactive power flow is similar to the pre-fault condition at the PCC as generator terminal voltage is compensated up to 100% during the voltage sag.

For more severe sags, the current rating of the SHUC and SERC will have to be increased to a higher value if 100% power has to be transferred at PCC. Though this is technically possible it may not be desirable as the rating is already derived for the worst case voltage scenario as required by the Grid Code.

6.5 The performance of a STATCOM in VAR control mode

The switch SW1 in Fig. 2 is closed to put voltage compensator of the UPQC out of operation. Under this condition the shunt compensator of the UPQC acts like a STATCOM in VAR control mode. The performance of the STATCOM for the system shown in Fig. 2 is presented in this section. A similar fault condition is created as in section 6.1, which creates a voltage sag to 15% at PCC. The breaker resistor is operated as in the UPQC case study. The minimum rating of the STATCOM required to aid fault ride through of the FSIG has been found to be 1.72pu. The relevant results are shown in Fig. 15. The reactive power demand of the machine is very high after the fault is cleared. The STATCOM helps the FSIG to build its terminal voltage, but takes a longer time to establish the normal operating condition compared to UPQC. If the STATCOM rating is reduced further, the generator fails to ride through the fault. The results can be seen in Fig. 16.

7 Conclusions

The application of UPQC in providing additional fault ride through support and VAR support to the wind driven FSIG has been investigated in this paper as per Irish Grid Code requirement. During normal operation SHUC of the UPQC maintains a unity power factor condition at the PCC. When a voltage sag occurs due to grid side fault the SERC of the UPQC can inject appropriate deficit voltage to prevent over speeding of the FSIG and the SHUC of the UPQC provides additional VAR support required during fault. The advantages of application of a UPQC over other FACTS devices are indefinitely long critical clearing time and 100% real power transfer for lower sag levels. On the cost aspect it has been shown that the installation cost of the UPQC for this type of application can be reduced by appropriately limiting the rating of individual compensators of the UPQC. The general principle developed in this paper (Fig. 13) to choose the rating of compensators can reduce the UPQC rating by 10% without compromising on the overall expected performance of the equipment. The performance of the UPQC is compared to that of a STATCOM in VAR control mode on same network and FSIG operating condition. The rating requirement of the STATCOM (1.72pu) is higher than the rating requirement of a UPQC (1.47pu) for the FSIG to comply with the Irish Grid Code. The UPQC proves to be a potential solution to the grid integration problems faced by the wind driven FSIG.

Appendix I

System parameters

Base value considered are V_{base}=690V,

S_{base}=2MW

FSIG(in pu)

Stator resistance (R_s)=0.00486

Rotor resistance (R_r)=0.00547

Stator reactance (X_{ls})=0.0919

Rotor reactance (X_{lr})=0.099

Magnetising reactance (X_m)=3.93

Lumped inertia constant (H)=3.5s

Power Factor Capacitor (PFC)= 4000µF

Slip = -0.006

UPQC

L_{SHUC}=0.13 pu

DC link capacitor=4000 µF

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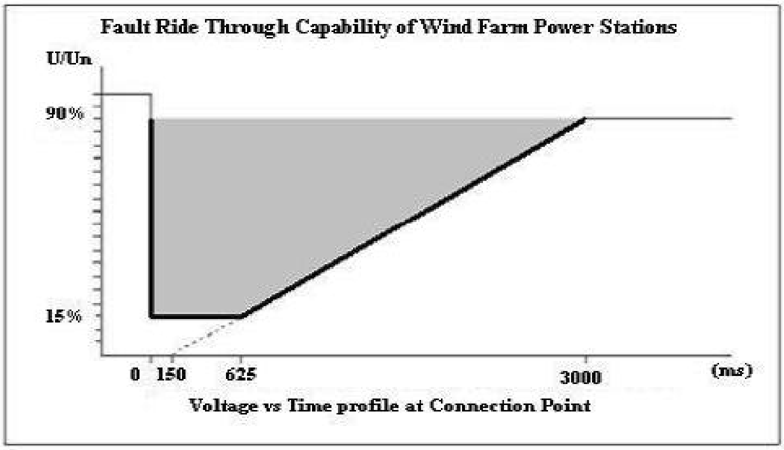

Fig.1 Fault ride through capability of wind generator under Irish grid code.

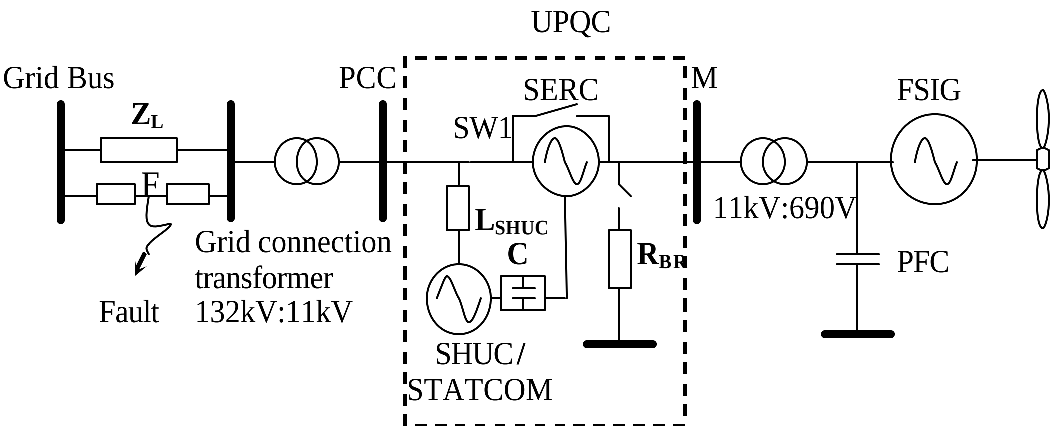

Fig. 2 Model configuration

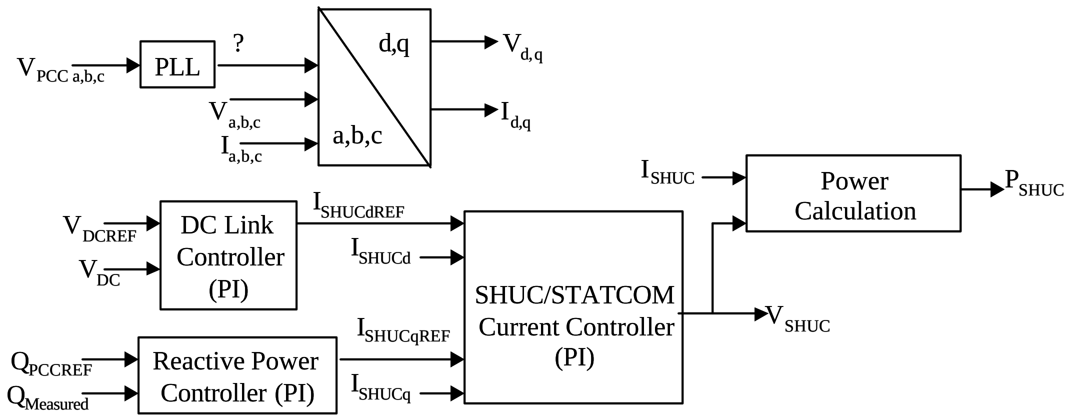

Fig. 3a SHUC/STATCOM control

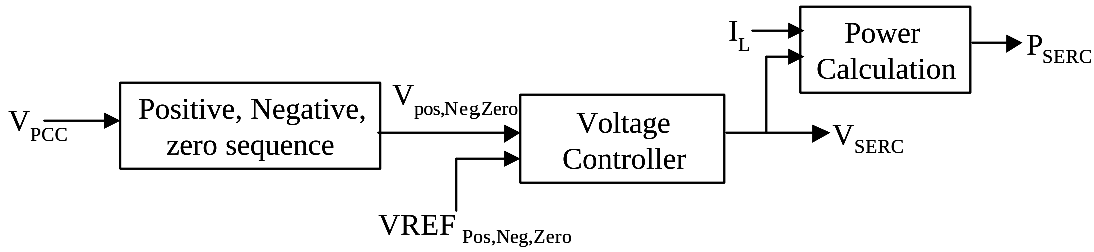

Fig. 3b Series compensator control

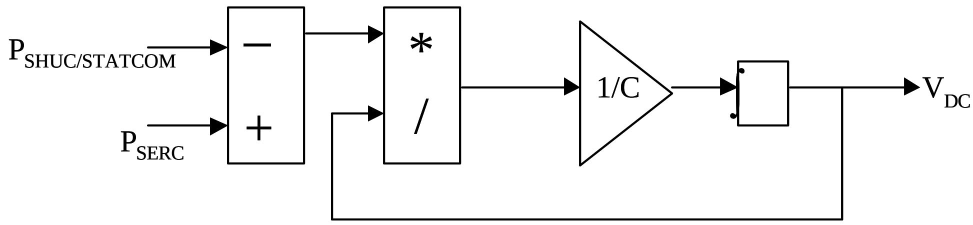

Fig. 3c DC link model

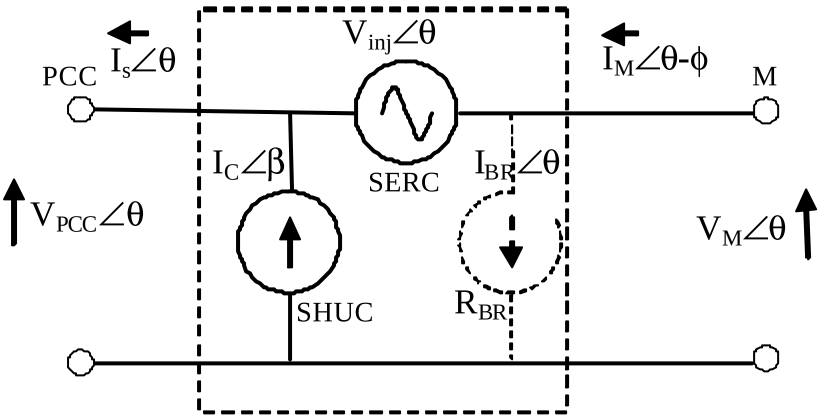

Fig. 4 Fundamental frequency representation of UPQC

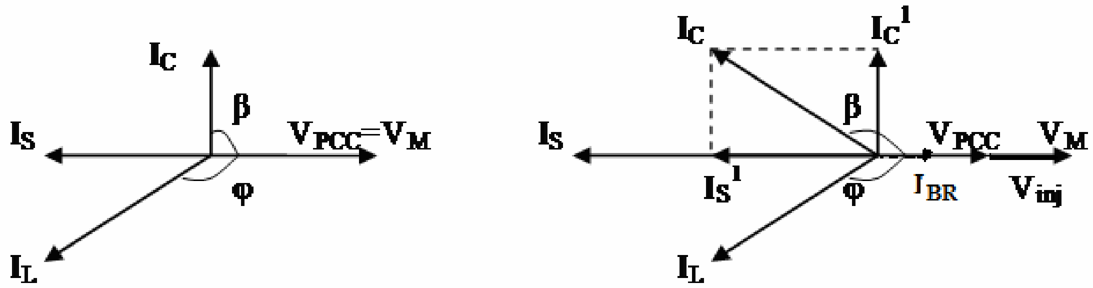

Fig. 5a,5b Vector diagram of UPQC under normal and abnormal operation

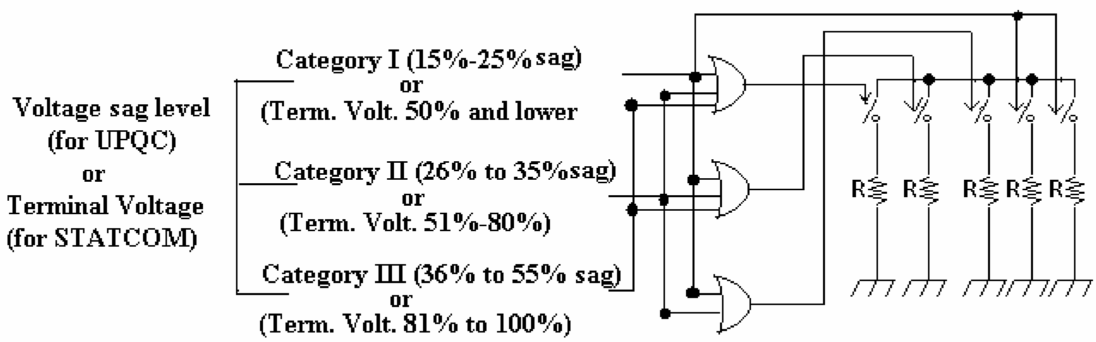

Fig. 6 Switching of breaking resistors condition

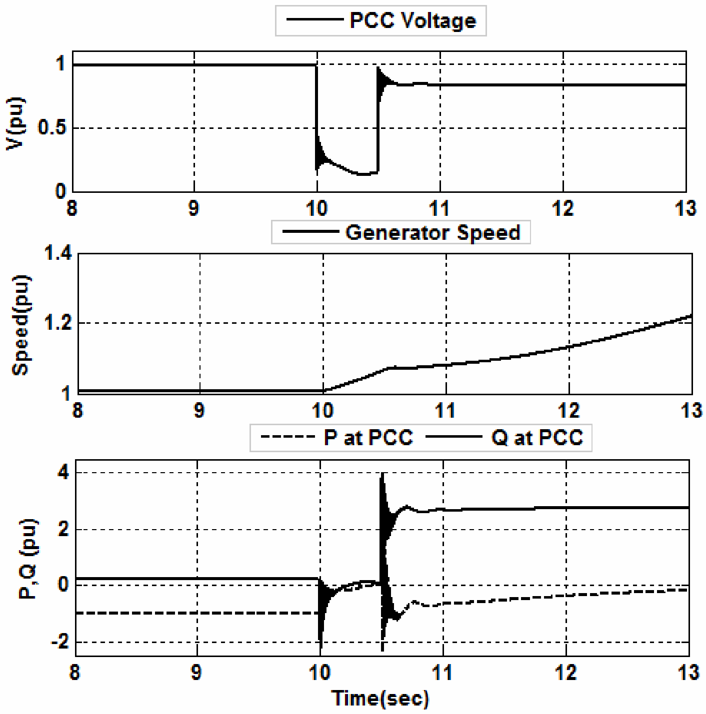

Fig. 7 The generator response to a three-phase fault without UPQC

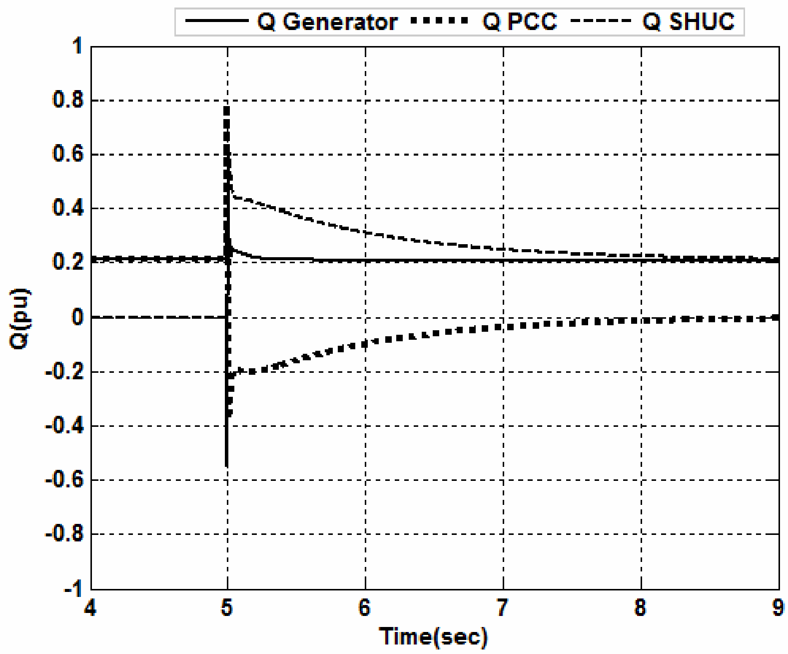

Fig. 8 Reactive support provided by the SHUC of UPQC at PCC

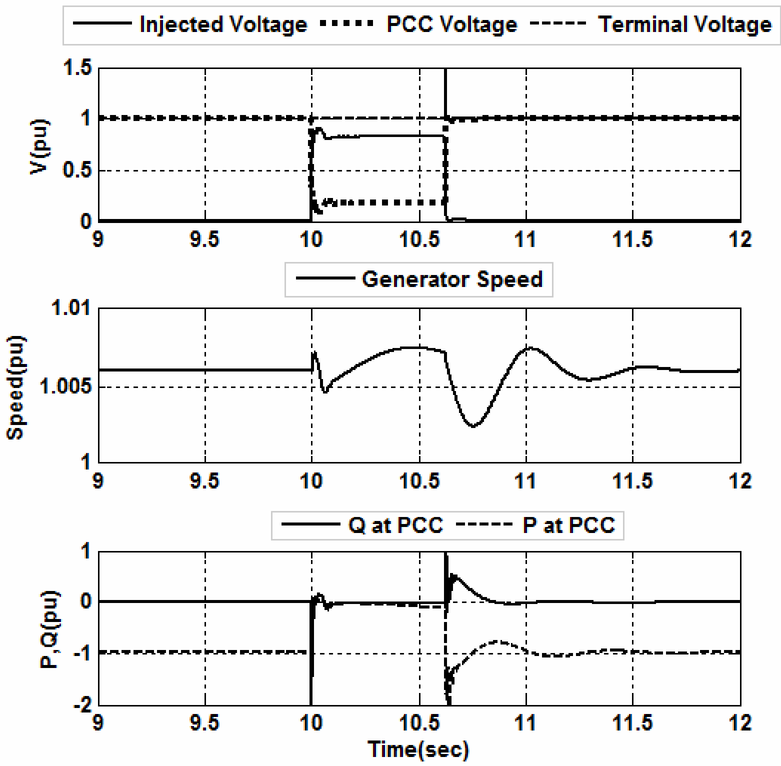

Fig. 9a Various voltage, speed and power responses to a three phase fault with UPQC

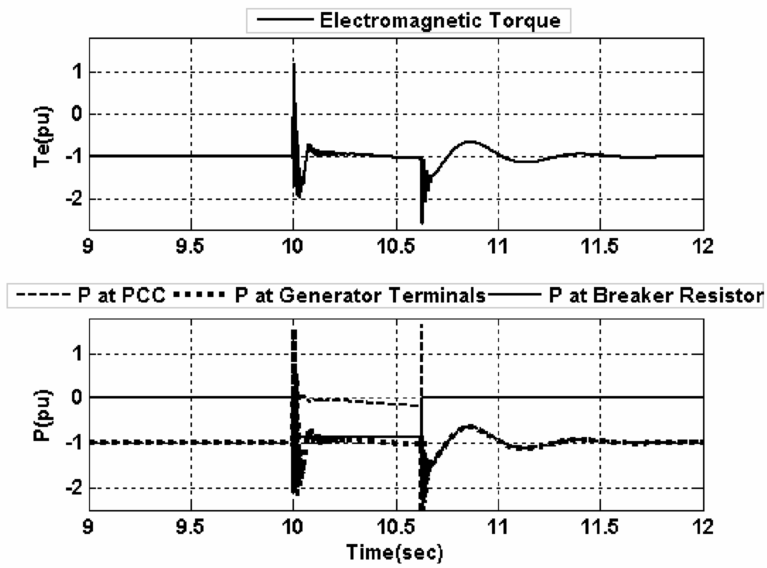

Fig. 9b Generator torque and power flow response to a three phase fault with UPQC

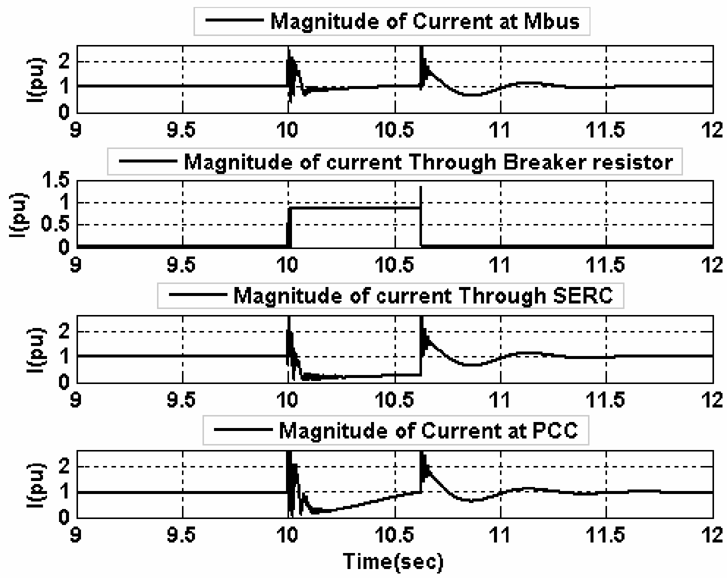

Fig. 9c Various current responses to a three phase fault with UPQC

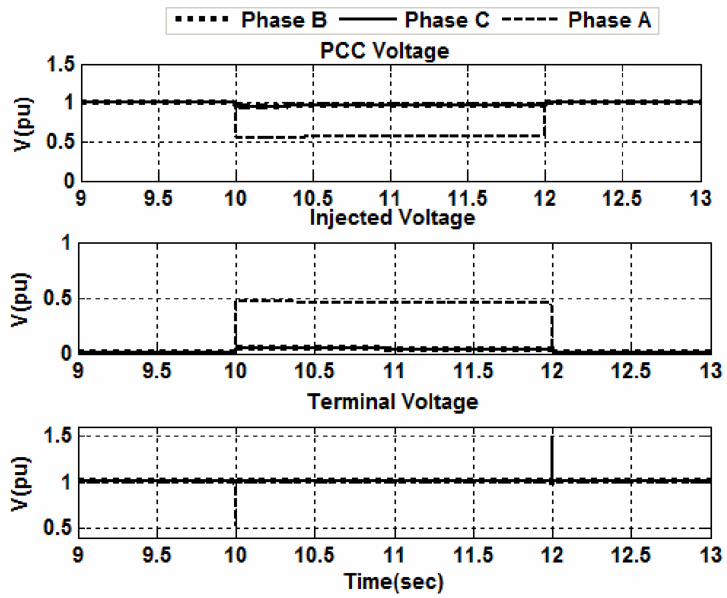

Fig. 10a Voltage profiles during a L-G fault at A phase

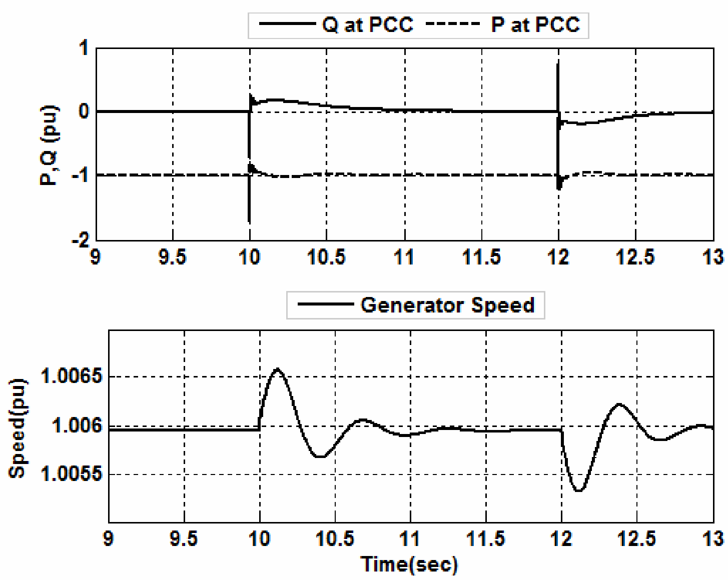

Fig. 10b Power flow and generator speed responses during a L-G fault at A phase

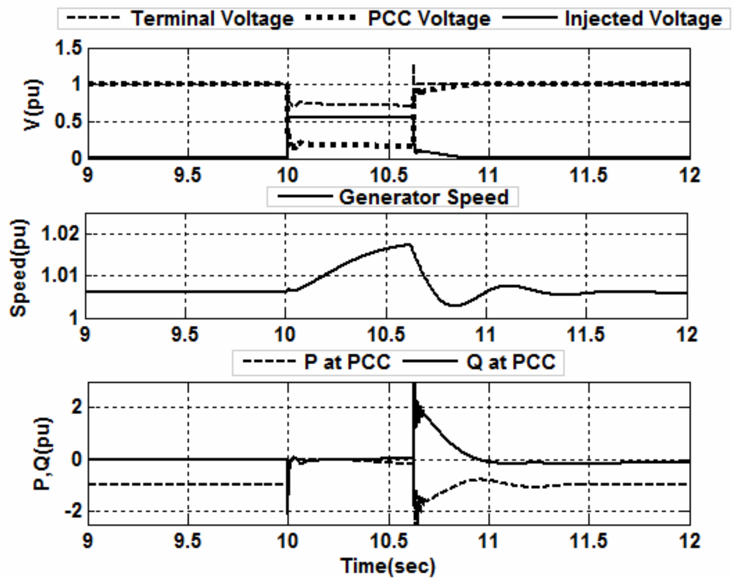

Fig. 11 Generator response to a three phase fault with limited voltage injection by the UPQC

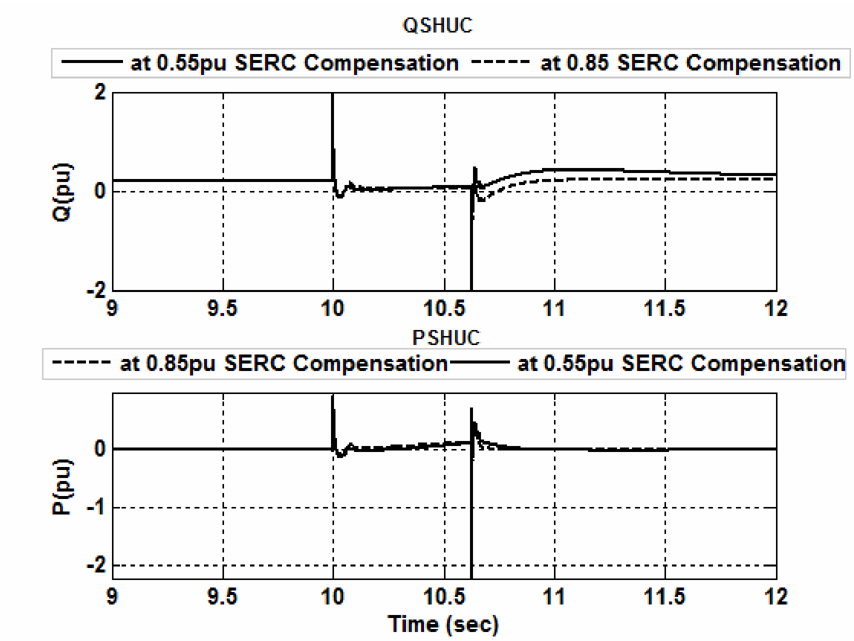

Fig. 12 Power flow through SHUC at full and partial voltage compensation

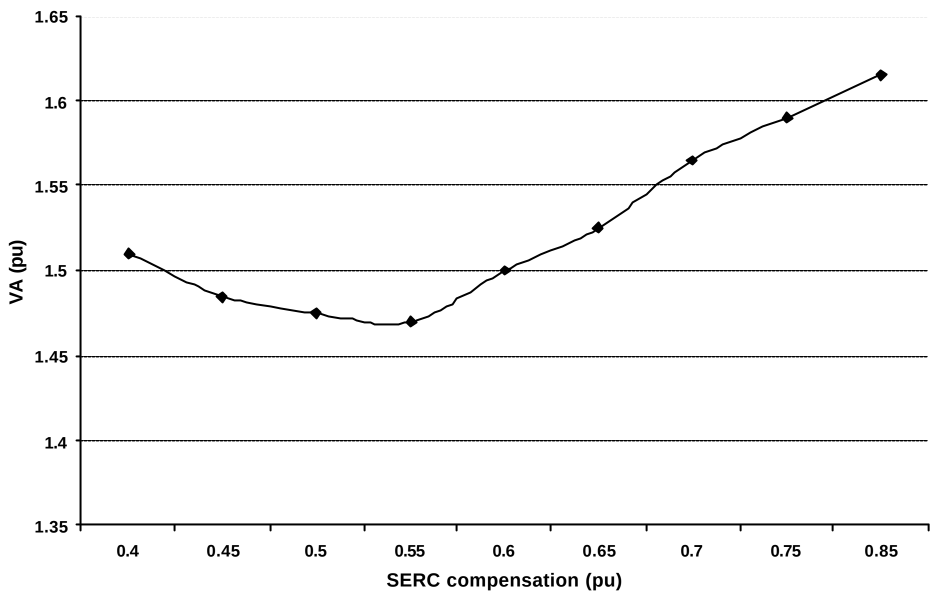

Fig. 13 VA rating curve of UPQC to 15% sag at PCC

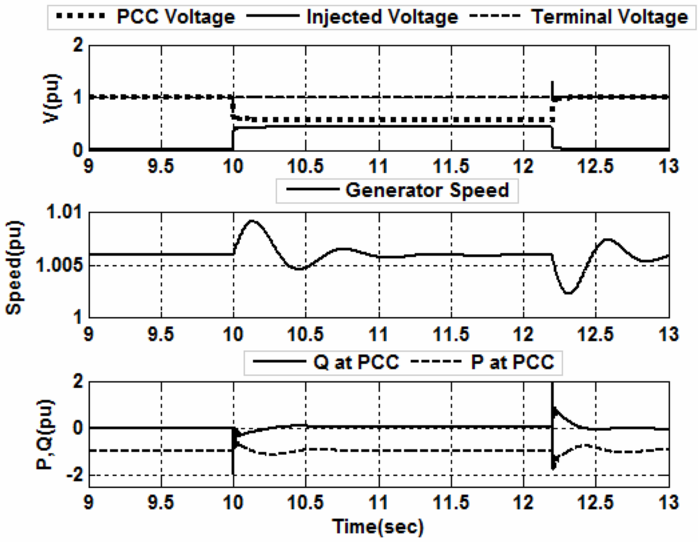

Fig. 14 Generator response to 55% voltage sag created by three phase fault

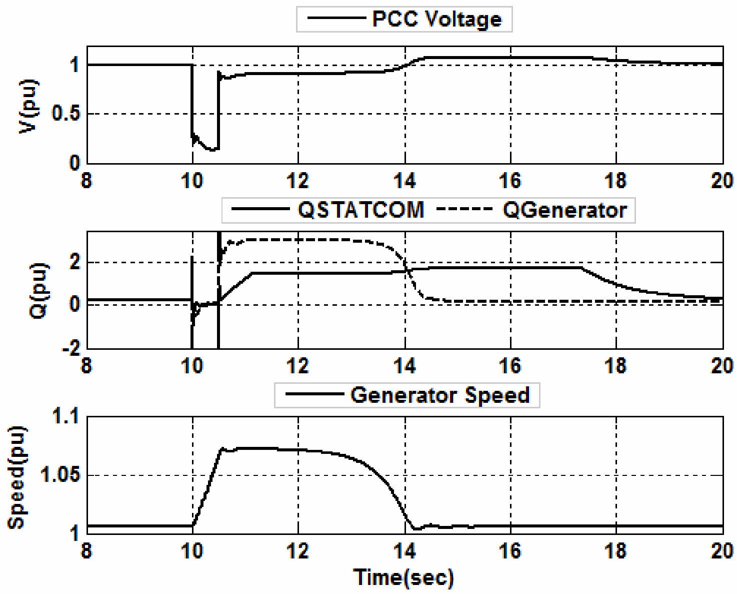

Fig. 15 Generator response to a three phase fault with STATCOM

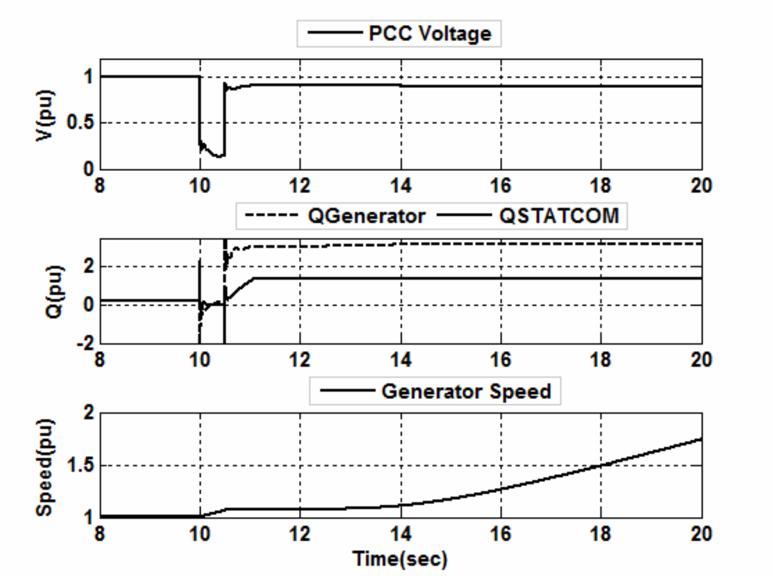

Fig. 16 Fault ride through failure of FSIG with lower rated STATCOM