Mansoura University
Faculty of Engineering
Mansoura Engineering Journal

Improving Fault Ride-Through Capability of Fixed-Speed Wind Turbine Using Combined Shunt and Series Compensation Scheme

تحسين قدرة عبور الخطأ لتربينة الرياح ثابتة السرعة باستخدام معوضات التوازى ومعوضات التوالى

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KEYWORDS:
Fault ride through, Fixed speed wind turbine, Static synchronous compensator, Static synchronous series compensator and Voltage source converter.

الملخص العربي:- **يقترح هذا البحث طريقة لزيادة قدرة تربينات الرياح ثابتة السرعة على عبور اخطاء الشبكة وذلك باستخدام تعويض التوازى أو تعويض التوالى حسب حالة انخفاض الجهد. تم عمل اسلوب مركب مبنى على طبولوجية ربط توالى وربط توازى لمحول مصدر جهد واحد بهدف زيادة امكانية عبور الخطأ لتربينة الرياح ثابتة السرعة. يعمل محول مصدر الجهد بطبولوجية ربط توازى كمعوض متزامن استاتيكى يقوم بتنظيم الجهد فى حالة التشغيل الطبيعى وفى حالة الهبوط البسيط فى جهد الشبكة عن طريق حقن قدره غير فعالة اما فى حالة الهبوط الشديد لجهد الشبكة تتحول طبولوجية ربط محول مصدر الجهد لحظيا من التوصيل التوازى الى التوصيل التوالى ليعمل كمعوض توالى متزامن استاتيكى يقوم بحقن جهد خلال محول ربط متصل على التوالى مع اطراف مولد التربينة وبالتالى يقوم بتعويض جهد الاطراف لمولد تربينة الرياح وبهذه الطريقه يتم تلاشى تأثير اخطاء الشبكة على مولد التربينة وتبقى التربينة متصلة بالشبكه. فى نهج التحكم المقترح تم استخدام الحاكمات الموجبة والسالبة حتى تتمكن التربينة من عبور اخطاء الشبكة المتماثلة والغير متماثلة, وتم عمل محاكاة للطريقة المقترحة باستخدام برنامج PSCAD/EMTDC حيث اثبتت النتائج زيادة قدرة تربينة الرياح ثابتة السرعة على عبور اخطاء الشبكة المتماثلة والغير متماثلة.**

Abstract—**This paper proposes a fault ride-through (FRT) scheme with alternatively employing shunt and series compensation for enhancing FRT capability of the fixed speed wind turbine (FSWT). A combined approach based on shunt and series grid interface topology for one voltage source converter (VSC) is used to enhance FRT capability for the FSWT. The VSC in its shunt interface topology works as a static synchronous compensator (STATCOM) to regulate voltage in normal operation and in light voltage dip. In case of serious grid voltage dip the VSC instantaneously switches from shunt to series grid interface and works as static synchronous series compensator (SSSC) injecting a series voltage through series coupling transformer to compensate the terminal voltage of the wind turbine generator (WTG). The proposed control scheme, utilizing positive and negative sequence controllers, provides a transient management solution for both balanced and unbalanced fault conditions. A comprehensive simulation study using PSCAD/EMTDC simulation program demonstrate the performance of the proposed scheme for enhancing the FRT capability of the FSWT in response to severe symmetrical and asymmetrical grid faults.**

I. INTRODUCTION

The continued growth of the wind power generation makes the operational aspects of the wind turbines with the grid such as terminal voltage regulation, voltage unbalance and FRT capability acquire a great interest in the recent grid codes. During the normal operation the voltage regulation can be achieved by controlling the reactive power and during the fault conditions enhanced FRT capability is required to enable the wind turbines to remain connected to the grid even when faults occur. Since FRT performance is among the critical concerns in the recent grid codes, the wind turbines technical development has moved from the fixed speed concept with squirrel cage induction generator (SCIG) that exhibits relatively poor performance during the fault conditions to the variable speed concept with either doubly fed induction generator (DFIG) or permanent magnet synchronous generator that employ back to back voltage source converter. These new types of wind turbines

Received: 2 December, 2015 - revised: 9 February, 2016 - accepted: 19 April, 2016.

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are capable of providing voltage support to the grid, but the FSWT based wind farm still represents the highest penetration of the installed wind power capacity. FSWT utilizes SCIG that is directly connected to the power system; the electrical torque of the SCIG is directly proportional to the square of the grid voltage. In case of grid fault the generator terminal voltage is reduced, so that the electrical torque is reduced. If the mechanical torque remains constant during the fault, the generator will accelerate and the slip will increase [1]. The operation at increased slip results in high absorption of reactive power by the generator. Especially after the fault clearance, high amounts of reactive power are needed in order to build up the generators magnetic field [2], [3]. As a consequence, the terminal voltage may not be able to fully recover [4]. In some circumstances, unless the generator is disconnected, the described situation could lead to voltage instability and in the worst case, to a voltage collapse in the whole system [5]. Therefore additional devices or FRT technique should be incorporated to prevent these types of instabilities and make the FSWT grid compliant. Possible FRT support can be achieved using reactive power compensation methods, by installing additional devices such as (STATCOM) or static VAR compensator (SVC) either at the terminals of a wind turbine or at the substation to provide the required voltage support. [6], [7], [8]. STATCOM is identified to provide the best dynamic stability enhancement for FSWT, where it has flexible dynamic control capabilities [9], and it can help to integrate wind power plants in a weak power system [10]. The STATCOM can also perform an indirect torque control for the same kind of generators [11], [12] to decrease the mechanical stress during grid voltage dip, hence the STATCOM technology adds the missing functionality to wind farms in order to become grid-code compliant. The capability of STATCOM compared to SVC to increase the stability of fixed speed induction generator based wind turbines is given in [13] and [14]. But like regular shunt compensation, the shunt devices cannot fully isolate the wind park from serious voltage dips so as to achieve full system protection. Therefore, the series compensation is generally required to provide direct voltage restoration at the wind turbine terminals. For the series compensation the well-known flexible ac transmission systems devices (FACTS) such as, SSSC and dynamic voltage restorer (DVR) should be used. The SSSC has been proposed to isolate DFIG-based wind turbines from the grid in case of voltage dips in [15]. Also DVR is proposed to protect the DFIG wind turbine from the grid faults in [16], [17]. This series compensation has the potential to enhance FRT performance. But this topology requires employing an additional VSC at the generator terminals to perform series voltage compensation. And it is very expensive for full voltage compensation since the VSC must have the same power rating as the generator [18]. Therefore in this paper a combined approach based on shunt and series grid interface topology for one VSC is used to enhance FRT capability for the FSWT. The VSC in its shunt interface topology works as a STATCOM to regulate voltage in normal operation and in light voltage dip, and in case of serious voltage dip the VSC instantaneously switches from the shunt to the series grid interface and works as a SSSC to compensates the voltage, and maintains the stator voltage at its rated value.

TABLE I
POWER SYSTEM PARAMETERS

Generator data		Series connection	
Rated apparent power	2.35 MVA	Rated power	1MVA
Rated power	2 MW	Rated voltage	0.69 KV
Rated voltage	0.69 KV	Rated frequency	50HZ
Rated frequency	50Hz	Series trans. leak. React.	5 %
Stator resistance	0.066 PU	Dc link capacitor C_1,C_2	58500µF
1st cage resistance	0.298 PU	R_c	2000 Ω
2nd cage resistance	0.018 pu	R_b	0.2 Ω
Stator unsat. Leakge react.	0.046 pu	Step up transformer 0.69/20 KV	
Unsat. magnetizing react.	3.86 pu	Rated power	2.5 MVA
Rotor unsat. Mutual react.	0.122 pu	Rated frequency	50HZ
2nd cage unsat. react.	0.105 pu	$+ve$Sequence leakage react.	7 %
Inertia (J=2H)	45.7kg.m.m	Primary voltage	0.69 KV
Multimass model		Secondary voltage	20 KV
Machine rating	2.35MVA	Mag. Current	0.5%
frequency	50HZ	Grid	
Mech. Synch. speed	1000 rev/min	Rated voltage	20 KV
Turbine inertia constant	353.3kg.m.m	Rated frequency	50 HZ
Fixed capacitor banks		SCR & X/R	10&8
capacitor	7990 µF		
Shunt connection			
Rated power	1MVAR		
Rated voltage	0.69kv		
Rated frequency	50HZ		
R_{st}	0.0004Ω		
L_{st}	0.000107 H		
Dc link capacitor C_1,C_2	58500 µF		
R_c	2000 Ω		
R_b	0.2 Ω		

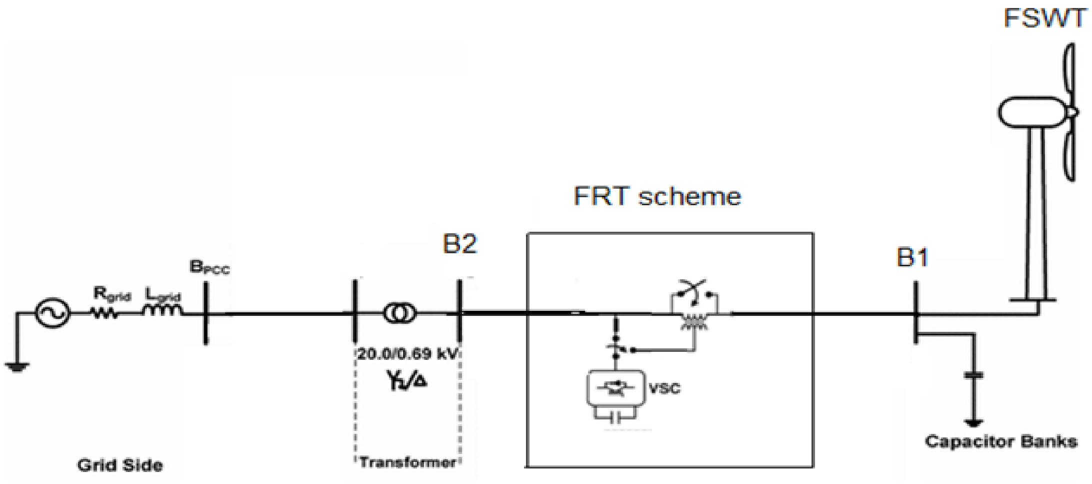

Fig. 1 Structure of the investigated power system: FSWT and VSC connected in shunt and series interface

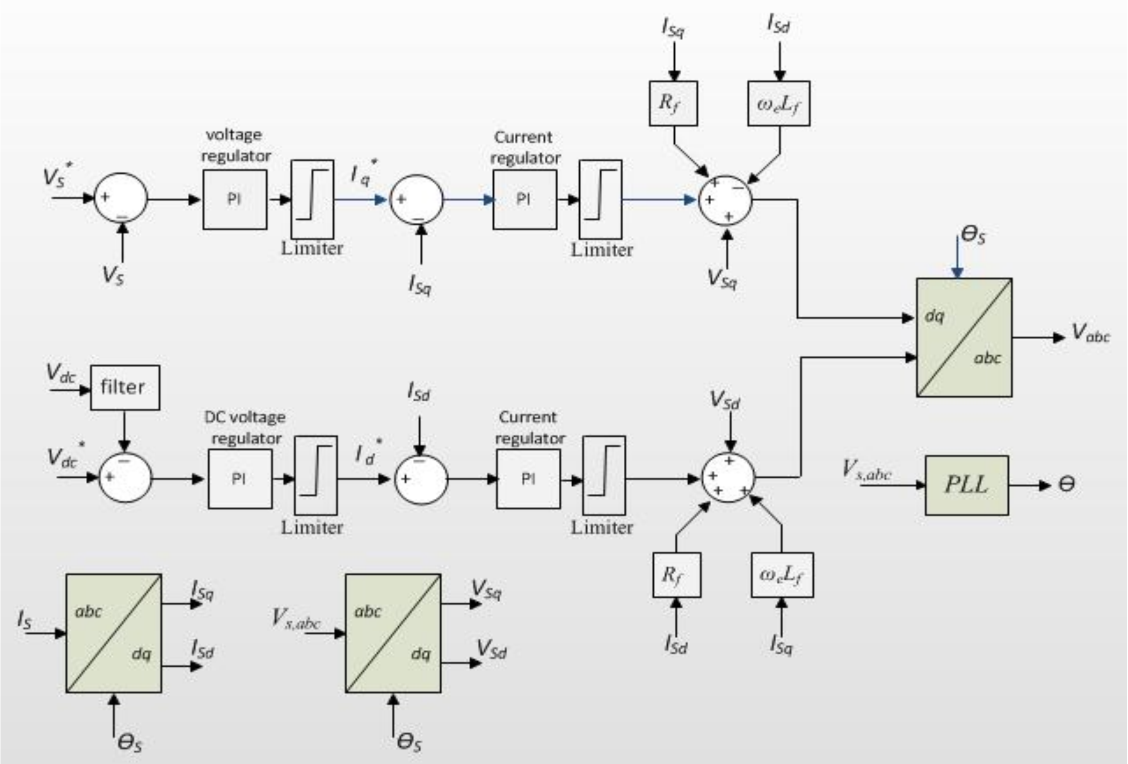

Fig. 2 STATCOM controller based on the voltage controller

II. POWER SYSTEM STRUCTURE

The investigated power system is shown in Fig. 1. The parameters of this system are listed in Table I. [19]. The VSC is connected to the grid via both shunt and series connections that can be controlled by three switches. The reactive power absorbed by the SEIG is compensated by fixed capacitor banks connected to each wind turbine and the STATCOM through the shunt interface topology. For the series path, a series transformer in parallel with a switch is connected between the SEIG and the grid terminal so that the voltage across the transformer can be inserted during grid disturbances. This transformer would have a turn's ratio of 1:1 and have a volt–ampere rating the same as the wind turbine.

III. FAULT RIDE THROUGH OF FSWT USING STATCOM

In this mode the controller of the VSC in the shunt interface topology uses the terminal voltage of the WTG as a control input to generate or absorb the required reactive power to support the grid voltage where the voltage and current measurements at the generator bus are sampled and fed into the controller. In this study the average model of the STATCOM is used where it is much convenient for the study than the detailed model, as it enables to avoid detailed time series simulation and it will help to speed up simulation time [20]. So the switching converter replaced with controllable voltage sources with energy conservation with balancing the current on the DC side with current on the ac side. The power of the DC circuit of the STATCOM is controlled by controlling the DC link voltage. As shown in Fig. 2 the STATCOM control structure is based on the voltage-oriented vector control scheme [21] as usually applied to three-phase grid-connected converters. It is a cascade control structure with inner proportional integral (PI) current controllers in a rotating dq reference frame with grid voltage orientation. The current is decoupled into two control loops, and the reference grid voltage is utilized to generate the q –axis reference current, and the DC-link voltage is maintained by controlling the d-axis current to compensate the active power losses, so that by controlling STATCOM direct and the quadrature current, the active and the reactive power exchange between the converter and the ac-system, respectively can be controlled. After that the current error signals are then fed into the current regulator and the output of the current regulators are the voltage signals V_d and V_q which are added to the feed forward signals of the Park transformed three phase terminal voltages. After that the voltage drop across the converter inductors are added to the controlling voltage signals. During the fault condition (FRT operation), the STATCOM injects the full quadrature current I_{qref} to support the grid voltage, and the DC-link voltage is regulated in acceptable range based on the deployed current limiter among I_{qref} and I_{dref} .

IV. STATCOM CONTROL SCHEME EVALUATION

The effectiveness of the proposed shunt compensation topology is verified using PSCAD simulation program. The performance and the transient behaviors of the VSC in shunt with FSWT are investigated in response to symmetrical grid fault at the point of common connection (PCC) in two cases of 70% and 40%voltage dip. Fig. 3 shows the simulation results for the two cases of the voltage dip. The fault occurs at the grid side and starts at the moment of 10 s and lasts for 150ms. For the two cases of voltage dip, STATCOM increases its reactive power output as shown in fig. 3(a). For the case of 70% voltage dip no significant impact is monitored on the waveforms of the generator current as shown in fig. 3(b), also Fig. 3(c) and (d) illustrates smooth waveforms of the FSWT output power and rotor speed and the DC link voltage is properly regulated during the fault, as shown in Fig. 3(e). But for the case of 40%voltage dip although the VSC injects its maximum reactive power output as shown in fig. 3(a) and helps the system to remain stable where the generator can return to normal operation after the fault clearing, but the generator current is increased as shown in fig 3(b), and the rotor speeds up to a high speed as shown in fig. 3(d) because the main problem in this case is that the WT unable to supply the generated active power to the grid, and this will cause a high stress on the mechanical parts of the WT and leading to WT disconnection from the grid. This ensures that in case of serious grid voltage dip, the series compensation should be employed to avoid the lack of the active power evacuation in to the grid by this way the rotor speed can be maintained within accepted limits and the WTG can ride through the serious grid voltage dip

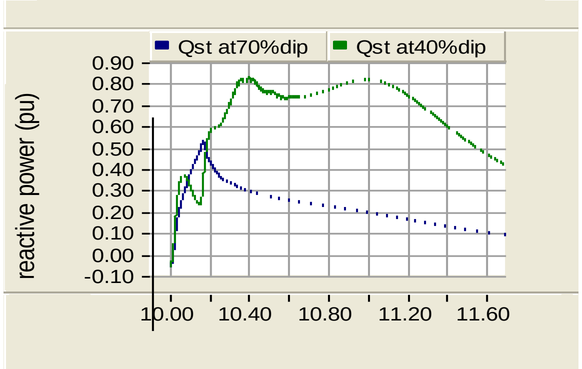

Fig. 3(a) STATCOM reactive power

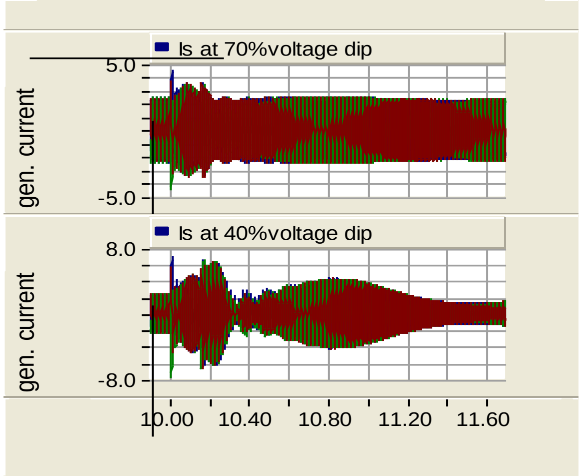

Fig. 3(b) Generator current

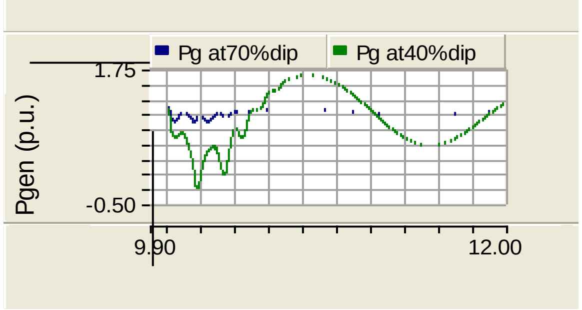

Fig. 3(c) Generator active power

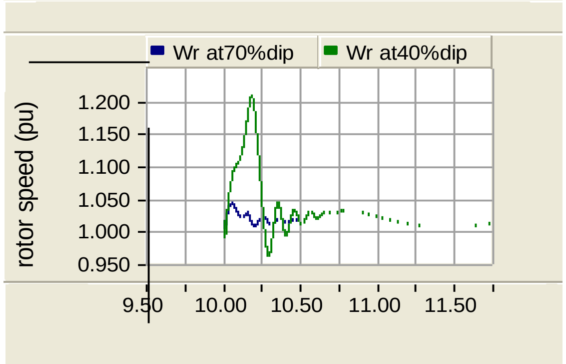

Fig. 3(d) Rotor speed

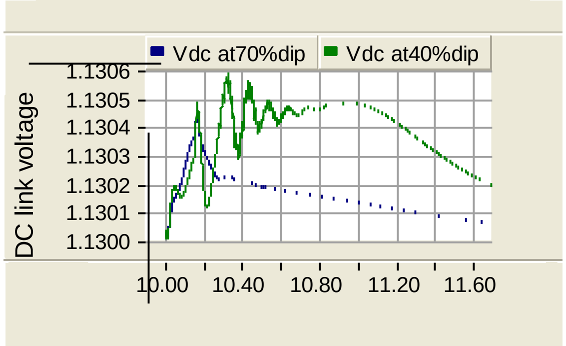

Fig. 3(e) DC link voltage

V. FAULT RIDE THROUGH OF FSWT USING SSSC

As shown in the previous section, In case of serious grid faults, shunt compensation cannot isolate FSWT and series compensation is generally required. In the series compensation mode the VSC is connected to the grid via a series coupling transformer and works as SSSC. In this study the average model of the SSSC is used [19]. The SSSC acts as a controlled voltage source injecting series voltage across the series coupling transformer, the active power of the generator is evacuated through the SSSC, and can be expressed as (1)

$$P_{series} = \left(\frac{V_{prefault} - V_g}{V_{prefault}}\right) P_{gen.} \qquad (1)$$

Where Vpre-fault is the pre-fault grid voltage, Vg is the measured grid voltage and Pgen. is the generated power. Equation (1) indicates that in case of zero voltage dip occurred at full power generation the VSC should absorb WTG rated power. At this case proper short term overloading capability may be considered as effective solution of the converter rather than installing a higher rated VSC [19]. Due to the power evacuation through the SSSC, the DC link voltage will increase. Therefore a DC link braking resistor is added to dissipate the active power absorbed and maintain the DC link voltage [22], [23]. Fig. 4 shows a detailed control diagram in the dq reference frame of the SSSC controller, which can be described in the following steps:

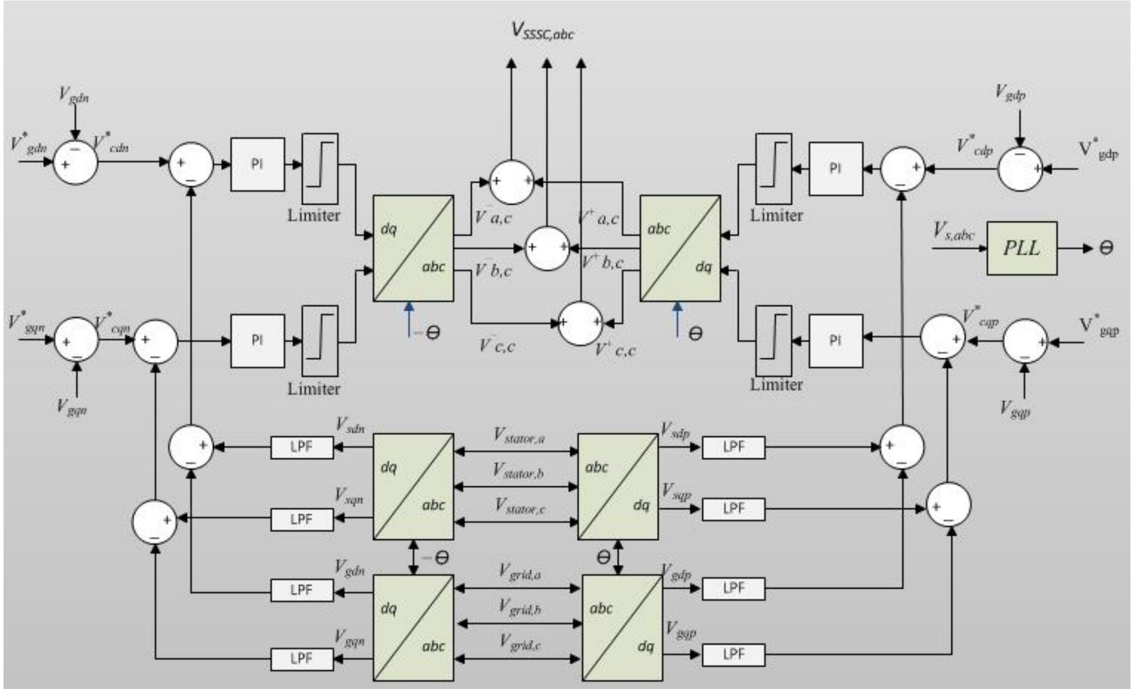

Fig.4 SSSC controller in positive- and negative-sequence reference frame

1) The phase locked loop (PLL) is used to determine the synchronizing phase angle (θ) of the stator voltage to develop a dq reference frame.
2) The direct and quadrature grid voltages V_{gd} and V_{gq} pre and during the fault period is calculated.
3) The reference voltages of the SSSC $\left(V^{+}_{SSSCdq,ref}\right)$ $\left(V^{-}_{SSSCdq,ref}\right)$ are defined based on a phase invariant injection method [24], where the reference compensation

voltages are considered as the differences between pre fault grid voltages $\left(V_{gdq,ref}^{+}\right)$ $\left(V_{gdq,ref}^{-}\right)$and measured grid voltage during the fault $\left(V_{gdq}^{+}\right)$ $\left(V_{gdq}^{-}\right)$ and can be expressed as:

$$\begin{bmatrix} V_{SSSCd,ref}^{+} \\ V_{SSSCq,ref}^{+} \\ V_{SSSCd,ref}^{-} \\ V_{SSSCq,ref}^{-} \end{bmatrix} = \begin{bmatrix} V_{gd,ref}^{+} \\ V_{gq,ref}^{+} \\ V_{gd,ref}^{-} \\ V_{gq,ref}^{-} \end{bmatrix} - \begin{bmatrix} V_{gd}^{+} \\ V_{gq}^{+} \\ V_{gd}^{-} \\ V_{gq}^{-} \end{bmatrix} \tag{2}$$

4) The measured injected voltage across the series coupling transformer is compared with the calculated compensation voltage and the error fed into the voltage regulator
5) After that both direct and quadrature components of the converter voltages are used to determine $\left(V_{SSSC,abc}^{+}\right)$ and also the negatives sequence dq controlling voltages are transformed to $\left(V_{SSSC,abc}^{-}\right)$ while considering the transformation at $(-\theta)$, hence it will be added to $\left(V_{SSSC,abc}^{+}\right)$ to obtain the controllable injected voltage signal $\left(V_{SSSC,abc}\right)$ that is inserted through the series coupling transformer as shown in Fig. 4. Thus, it controls the injected series voltage based on the desired injected voltage. Consequently, the WTG terminal voltage is maintained constant and the transient of generator current will be mitigated even during a serious symmetrical and asymmetrical grid faults

VI. SSSC CONTROL SCHEME EVALUATION

The effectiveness of the proposed series compensation topology (SSSC) to isolate FSWT generator from serious grid faults is investigated in response to a severe symmetrical grid fault at PCC. The simulation results conclude that the SSSC demonstrate good performance for maintaining the generator terminal voltage during the fault by injecting series compensation voltage. Fig. 5 shows the simulation results in the case of three phase voltage dip of 0.01% for duration of 150 ms. The performance of the proposed series compensation topology is demonstrated by comparing the results with the case in which no compensation is applied. Without the series compensation the rotor speeds up to a high speed due to the sudden decrease in the electrical output power of the generator during the fault period, more over the generator losses its stability after the fault clearing as shown in fig. 5(b) and 5(c), and this will lead to wind turbine disconnection from the grid. But when the series compensation is applied, the voltage dip at the terminal of the WTG is mitigated where the SSSC is injecting a voltage in series with the generator terminal, as shown in Fig. 5(a) consequently, it will help to enhance the transient stability margin especially when the wind park connected to a weak grid. Also with the proposed series compensation topology a better damping for power oscillation with smooth power evacuation is achieved, as shown in Fig. 5(b). The control arrangements of the SSSC significantly contribute to improve the transient behavior of the wind turbine and provide better damping for power system oscillation and generator speed, Fig. 5(c). And it can be observed for the electrical torque in Fig. 5(d). By increasing the terminal voltage during the fault, the mechanical stresses will be released with smooth power flow and WTGs are able to survive disturbances by longer durations.

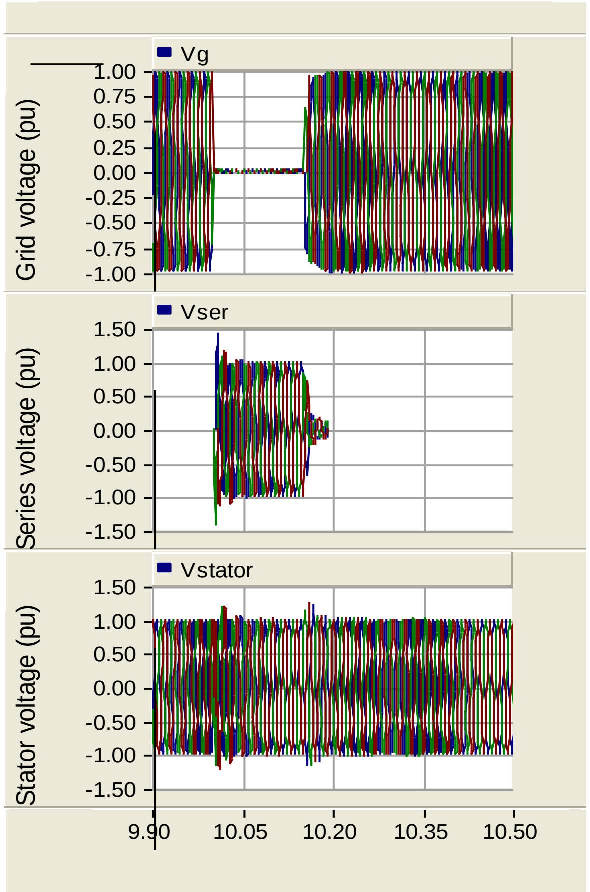

Fig. 5(a) Grid voltage, injected series voltage and stator voltage

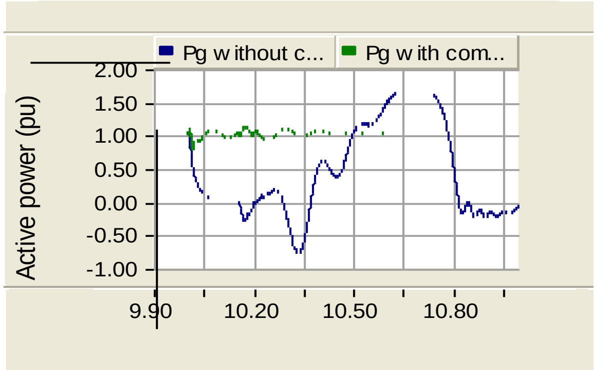

Fig. 5(b) Generator active power

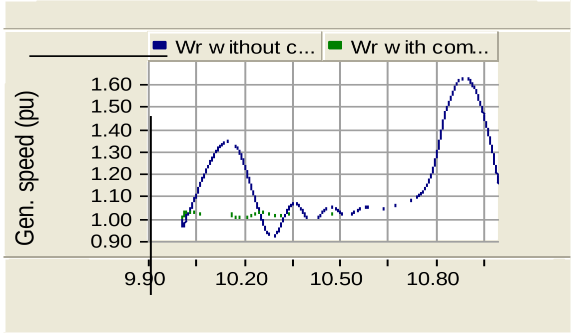

Fig. 5(c) Rotor speed

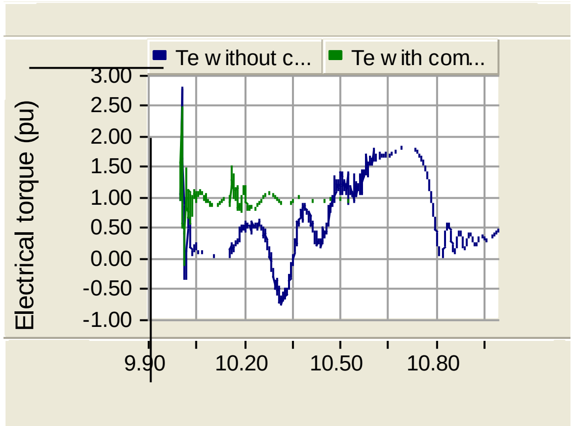

Fig. 5(d) Electrical torque

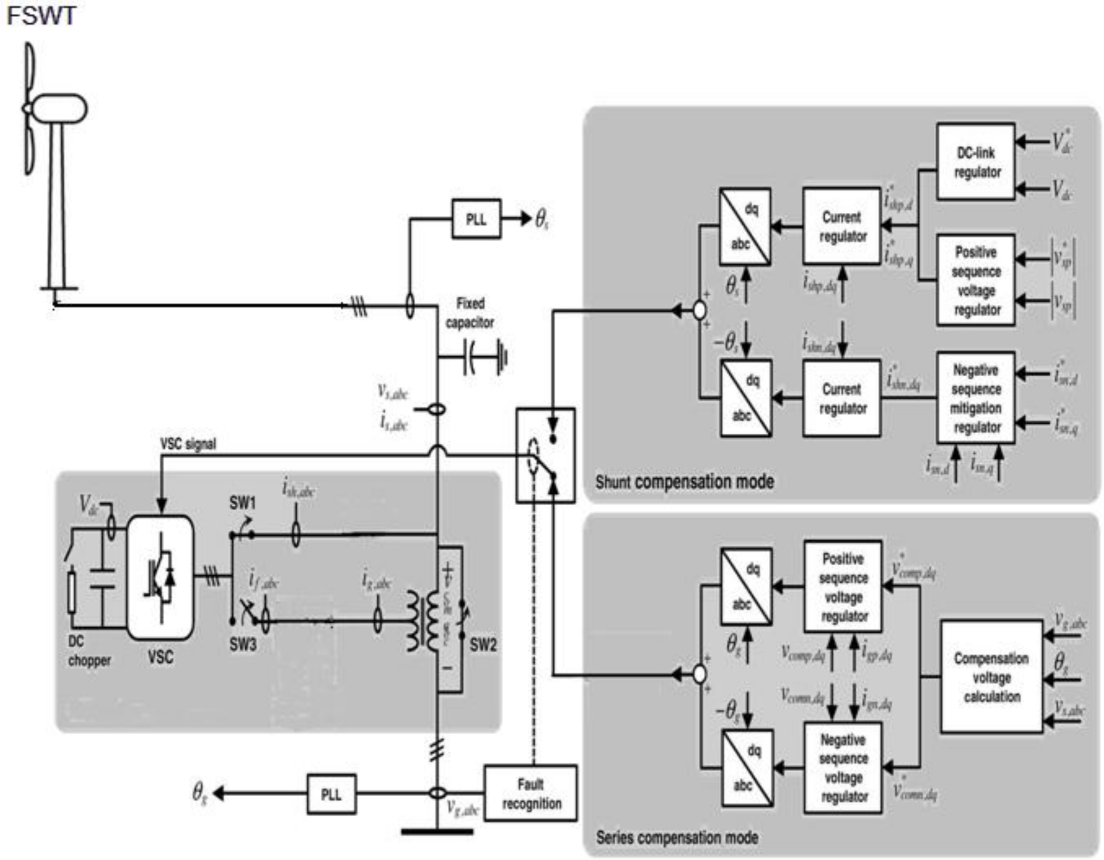

Fig. 6 simplified control diagram of the FSWT with shunt and series connected VSC

VII. FSWT FRT USING COMBINED APPROACH OF SHUNT AND SERIES GRID INTERFACE TOPOLOGY FOR ONE VOLTAGE SOURCE CONVERTER

Based on the previous sections the configuration of the proposed combined approach to regulate terminal voltage in normal operation and to isolate WTG from serious voltage dip by using one voltage source converter is designed as shown in Fig. 6. In normal operation, the wind turbine terminal voltage is varying a lot due to the wind speed fluctuations, so that the VSC in the shunt interface topology will work during normal operation to maintain constant voltage at the wind turbine terminal by injecting or absorbing reactive power working as a STATCOM. The shunt compensation will also work during the light grid voltage dip condition where at this case the shunt compensation is sufficient to supply enough reactive power to support the grid voltage, as shown in fig. 6 the shunt path is connected by switching on SW1 meanwhile, SW2 is closed to bypass the current through the series transformer, and SW3 is opened so that the converter is not affected by the series path, also the controller of the VSC is switched to the shunt compensation mode. But when a serious grid fault happens, the system instantaneously switches from shunt to series compensation mode working as SSSC, by opening SW1 and SW2 and SW3 is closed to let the current flow through the series path; also the controller will switch to the series compensation mode. The reconfiguration of the compensation system is triggered by a certain threshold in the grid voltage to avoid abnormal operation. Therefore voltage deviation between the stator and the grid $V_{com,abc}$ can be compensated to maintain the stator voltage at the pre-fault condition. The reconfiguration of the system can assist in maintaining the stator voltage as pre-fault conditions in which the WTG can continue on the normal operation, so that no additional protection schemes are required. While the positive-sequence voltage compensation leads to an increased voltage stability of the wind turbine, the negative-sequence voltage compensation leads to a reduction of torque ripple, increasing the lifetime of the generator drive train. Therefore, a specific negative sequence controller for shunt and series compensation has been designed and investigated in order to perform a good regulation of stator terminal voltage.

VIII. COMBINED APPROACH CONTROL SCHEME EVALUATION

The effectiveness of the proposed combined approach of series and shunt compensation topology rated at 0.69 KV is investigated in response to a severe symmetrical and asymmetrical grid fault at PCC. The objective of the reported cases is to demonstrate the impact of this combined approach on improving the FRT capability of FSWT connected to a weak grid by using one voltage source converter. Fig. 7 shows the simulation results for three phase to ground fault at the PCC at instant t = 10s for duration of 150ms. The effectiveness of the proposed series compensation is verified by comparing the results with the case in which no compensation is applied. Without compensation, a significant short-circuit current is induced at the stator terminal and the rotor speeds up to a high slip, as shown in Fig. 7(g) and Fig. 7(d) respectively and this is unacceptable since the high slip may damage the rotor winding and the over current triggers the circuit breaker that will disconnect the wind turbine from the grid. When the proposed series compensation topology is applied, as shown in Fig.7(c), the stator terminal voltage is maintained by injecting a series voltage 7(b) to avoid voltage drop. Since the VSC has been switched to the series compensation mode, So that the required instant reactive power compensation of the STATCOM after clearing the fault is reduced, consequently, it will help to enhance the transient stability margin especially when the wind park connected to a weak grid. Furthermore, it achieves better damping for power oscillation with smooth power evacuation, Fig. 7 (e). These control arrangements of the combined approach significantly contribute to improve transient behavior of the wind turbine and provide better damping for power system oscillation and generator speed, Fig. 7(d) and it can be observed for the electrical torque Fig. 7(f), also by increasing the terminal voltage during the fault, the mechanical stresses will be released with smooth power flow and WTGs are able to survive disturbances by longer durations.

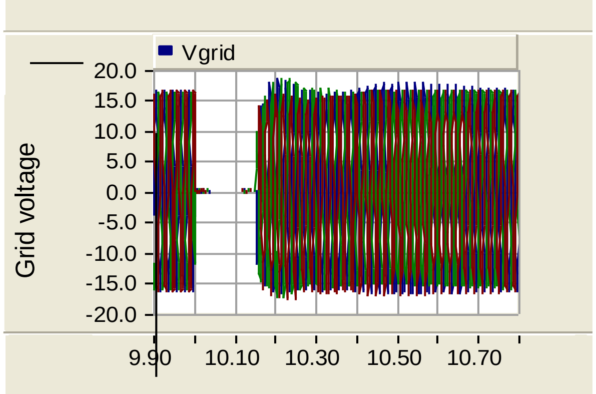

Fig. 7(a) Grid voltage

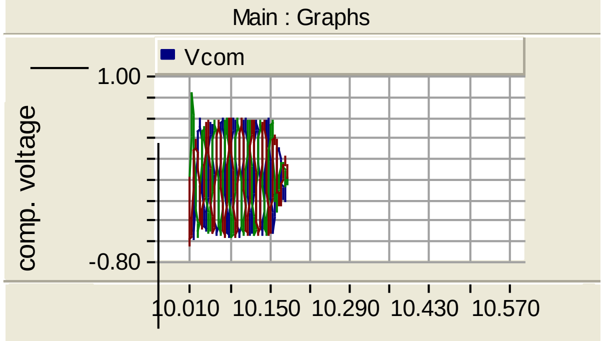

Fig. 7(b) Injected series voltage

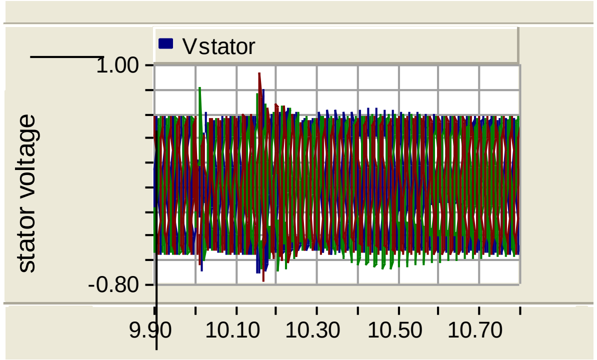

Fig. 7(c) Stator voltage

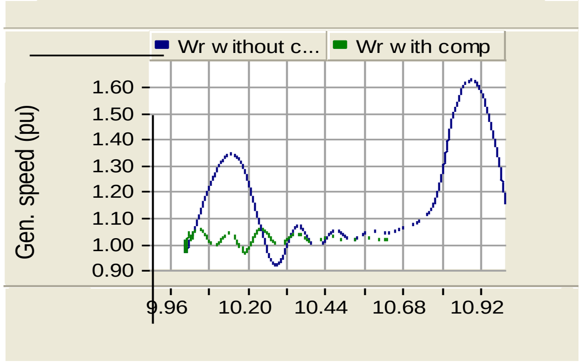

Fig. 7(d) Rotor speed

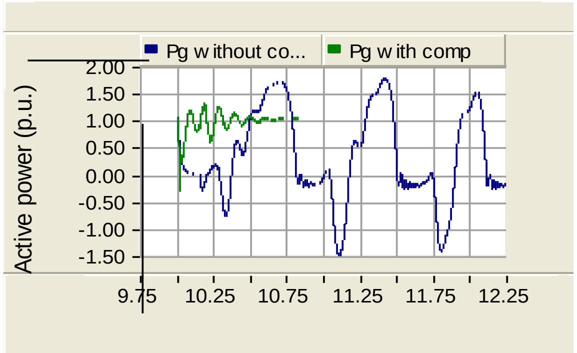

Fig. 7(e) Generator active power

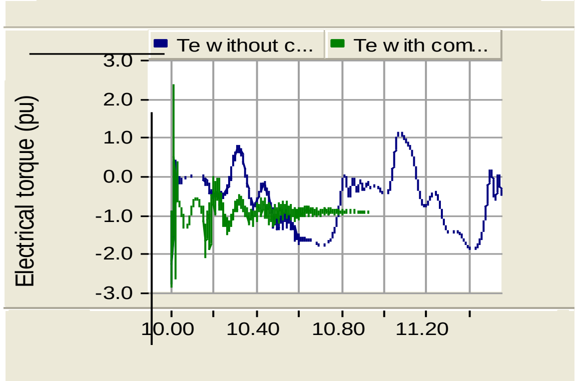

Fig. 7(f) Electrical torque

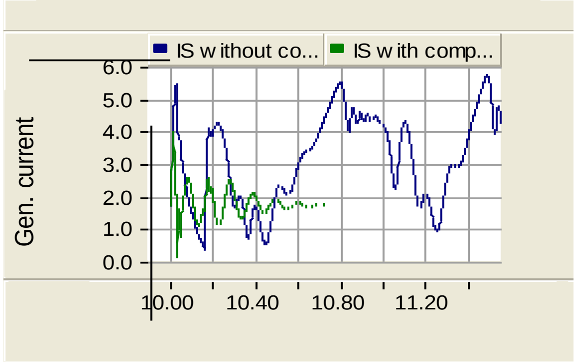

Fig. 7(g) Generator current

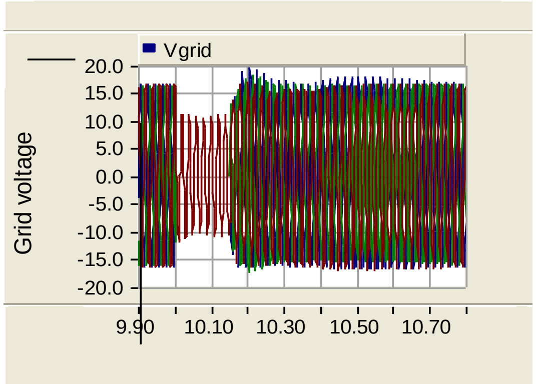

Fig. 8 (a) Grid voltage

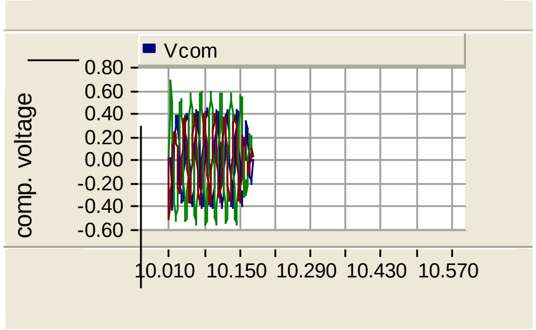

Fig. 8 (b) Injected series voltage

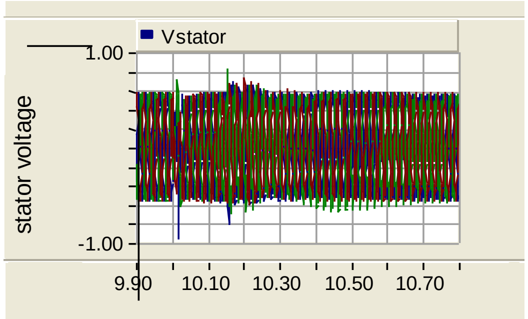

Fig. 8(c) Stator voltage

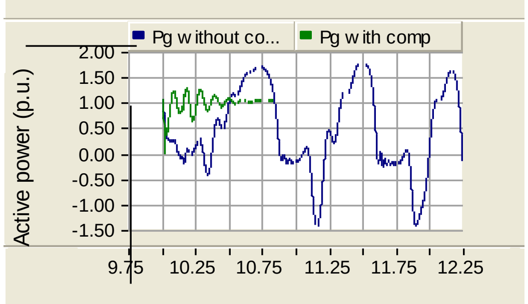

Fig. 8(d) Generator active power

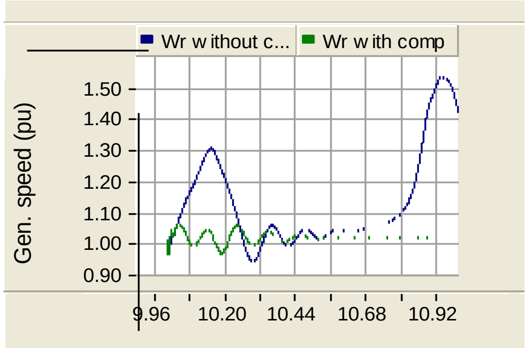

Fig. 8(e) Rotor speed

Also to verify the performance of the proposed combined approach in response to unbalanced voltage dip, the simulations have been performed for double-line-to-ground fault at PCC at instant 10 s and cleared after 150ms. The measurements are undertaken for the signals that demonstrate the function and performance of proposed schemes. When the unbalance voltage dip occurred, the system instantaneously switches to the series compensation mode where the voltage reaches to the threshold value. The proposed compensation scheme injects the desired unbalanced series voltage to minimize the voltage dip at the stator terminal as shown in Fig. 8(c) and maintains normal system operation, Furthermore, the active power production of the WTG is significantly enhanced with proper damping for the WTG speed as shown in Fig. 8 (d) and (e).

IX. CONCLUSION

In this paper a comparison between the potential of shunt compensation method and series compensation method to enhance fault ride through capability of the FSWT is carried out. Fault ride through scheme that can support both shunt and series compensation using one voltage source converter is proposed and it is considered an advantage from the economical point of view. The shunt compensation can support the grid voltage during the normal operation and light voltage dip but in case of serious grid voltage dip, the system is switched to the series grid interface injecting a series voltage through a series coupling transformer and maintains a constant voltage at the generator terminal. Also to enable the wind turbine to ride through the unbalanced grid faults, a negative sequence controller has been implemented. A comprehensive simulation study has been performed to demonstrate the effectiveness of the proposed fault ride through configuration.

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