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Simulation Studies on Integration of Voltage Source Converters (VSCs) In Weak Grids

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Abstract:

A New control topology is presented in this paper to have an effective integration of voltage source converters (VSCs) in weak grids. Even though the controller emulates the dynamic performance of synchronous machines and offers a smooth operation in many practical cases, it cannot ensure system stability in weak grids. Therefore to overcome the disturbance a supplementary nonlinear controller is developed to assist the linear controller and enhance system performance under very weak grids and fault ride- through conditions.

This paper presents a new control topology to enable effective integration of voltage source converters (VSCs) in weak grids. The controller has two main parts. The first part is a linear power-damping and synchronizing controller which automatically synchronizes a VSC to a grid by providing damping and synchronizing power components, and enables effective full power injection even under very weak grid conditions. The controller adopts cascaded angle, frequency and power loops for frequency and angle regulation. The controller emulates the dynamic performance of synchronous machines, which eases grid integration and provides a virtual inertia control framework for VSCs to damp power and frequency oscillations. Although the linear controller offers stable and smooth operation in many cases, it cannot ensure system stability in weak grids, where sudden large disturbances rapidly drift system dynamics to the nonlinear region. To overcome this difficulty, a supplementary nonlinear controller is developed to assist the linear controller and enhance system performance under large-signal nonlinear disturbances, such as self-synchronization, disturbances in grid frequency and angle, high power injection in very weak grids and fault-ride-through conditions.

*Key words -**Distributed generation, nonlinear control, power damping, and voltage source converter.***

I INTRODUCTION

The distributed generation [9] is used to refer to generation units that are connected to the distribution network rather than to the high voltage transmission grid. For reasons that are largely historical, the renewed popularity of DG after a period of hiatus is creating new opportunities for increasing the diversity and efficiency of our electricity supply, but is also challenging the established architecture of the networks.

Until the 1990s there had been a continuous process of building ever larger power stations to benefit from the economies of the scale, these power stations were located either close to the source of fuel, primarily coal, or in remote locations in the case of nuclear, this meant that the generators moved further away from the concentrations of load both geographically and electrically. However two other smaller-scale developments occurred that initiated the growth of DG. These were encouraged as part of the government's low carbon energy policy aimed at reducing the emissions linked to climate change.
To overcome demerits' of vector control of VSCs connected to very weak grids, the concept of power

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synchronization has been presented in and to provide an inherent synchronization with grid in steady-state similar to a synchronous generator (SG). Nevertheless, the proposed methods are synthesized based on small-signal dynamics and cannot guarantee large-signal stability. Among challenging issues facing DG integration is the DG connection to very weak grids (high impedance grids). Usually, the virtual inertia refers to a short-term energy storage which is added to a VSC. In the virtual inertia is emulated by proper dc-link control.

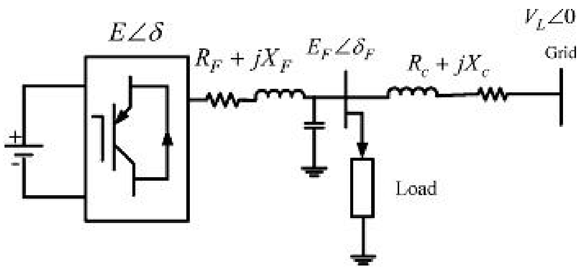

Fig. 1. Circuit diagram of a grid-connected VSC.

Motivated by the aforementioned challenges, a hybrid nonlinear control of VSCs in weak grids is proposed in this paper. The controller adopts a power synchronization loop with additional cascaded damping and synchronizing loops. The main characteristics of the proposed controller are
Summarized as follows:
1) The hybrid nonlinear power damping controller enables self-synchronization of a VSC in weak grids. This means that the controller does not need a separate synchronization unit and it automatically synchronizes itself with the grid. Self synchronization is a new concept, and its importance is more pronounced in weak grids. It should be noted that the process in still needs the inception time of synchronization and some information from the remote grid, thus it cannot realize a true plug-and play operation. Moreover, its performance and stability in weak grids have not been investigated. It is noticeable that during islanding, an MG may usually face permanent frequency drop representing considerable frequency and angle mismatch at the moment of reconnection, however, with the proposed controller system does not need any initial synchronization with grid and it realizes a plug and play system. This is the first time the concepts of Plug-and-play and nonlinear self-synchronization in VSCs are introduced.

2) The controller has cascaded frequency, angle and power loops. Therefore, better stability margin and damping characteristics can be achieved. This is a continuation of, where the concept of cooperative droop has been proposed. However, the method in demands accurate tuning of load angle and real power references, and lacks voltage regulation. In this paper, this problem is resolved by using a frequency loop as a first controller, therefore, the frequency reference is easily set equal to the grid nominal frequency.

3) Since the controller has a dynamic behavior similar to conventional SGs, it can be connected to very weak grids with SCR without loss of stability.

4) To guarantee system stability in all operating conditions especially when load angle drifts to the nonlinear region, a nonlinear supplementary controller is developed.

5) The controller is applicable to both modes of operation, i.e., islanded and grid-connected modes; therefore the need for islanding detection and system reconfiguration is automatically eliminated.

6) It provides fault-ride-through capability by proper adjustment of frequency, load angle and voltage amplitude, which in turn results in limiting current flowing into the interfacing circuit. It also automatically tracks and damps disturbances in main grid. The proposed control topology is general as it can be easily applied to VSC-based high-voltage dc (HVDC) transmission systems and DG units; however the main focus of this paper is on DG applications.

II. PROPOSED SCHEME

This paper focuses on the development of a nonlinear power damping control strategy for VSC units in weak grids with applicability to both grid-connected and islanded modes of operation. Fig. 1 shows the

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schematic view of a grid-connected VSC supplying a local load. The most critical issue for controller design is the complexity of the system due to nonlinear behavior of the power transfer dynamics. Usually, linear controllers are developed based on small-signal linearization; however, the control performance inherently depends on specific operating points. In this paper, a two-level topology with cooperative nonlinear and linear controllers is developed. The first level is a power synchronizing-damping controller. The second level is a nonlinear controller supporting the linear part to enhance system stability in weak grids or during self-synchronization where load angle is large and system works in the nonlinear region. It should be noted that the proposed outer loop controller can be also integrated with cascaded voltage-current control loops to ensure high power quality injection and inherent current limitation during faults. In this case, the synchronization angle for dq-frame transformation is obtained from the proposed outer-loop controller instead of a PLL as shown in Fig. 2.

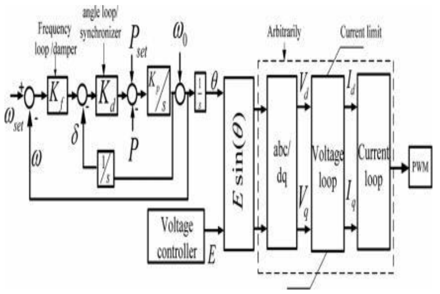

Fig. 2. Proposed linear control scheme.

Distributed generation (DG)

Distributed generation technologies can provide energy solutions to some customers that are more cost-effective, more environmentally friendly, or provide higher power quality or reliability than conventional solutions. Understanding the wide variety of DG options available in today's changing electric markets can be daunting. Some of these DG technologies offer high efficiency, resulting in low fuel costs, but emit a fair amount of pollutants (CO and NO); others are environmentally clean but are not currently cost-effective. Still others are well suited for peaking applications but lack durability for continuous output.

With so much to consider, it is often difficult for decision makers to determine which technology is best suited to meet their specific energy needs. DG technologies can meet the needs of a wide range of users, with applications in the residential, commercial, and industrial sectors. Decision makers at all levels need to be aware of the potential benefits DG can offer. In some instances, DG technologies can be more cost effective than conventional solutions. Among other things, DG can be used by utilities to both enhance existing systems and to delay the purchase of transmission and distribution equipment. In addition, DG units can help meet the changing demands of end users for premium, reliable or "green" power.

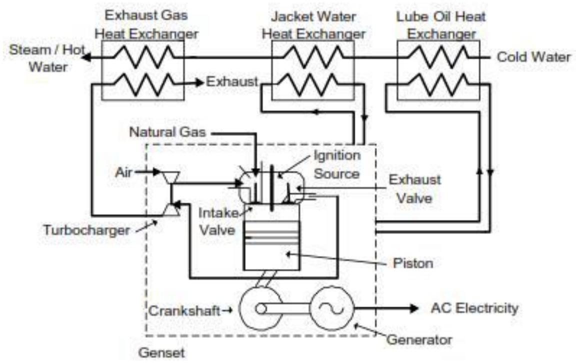

Fig 3 Reciprocating engine system

Reciprocating engines are ones in which pistons move back and forth in cylinders. Reciprocating engines are a subset of internal combustion engines, which also include rotary engines. Smaller engines are primarily designed for transportation and can be converted to power generation with little modification. Larger engines are, in general, designed for power generation, mechanical drive, or marine propulsion.

III. SYSTEM MODELING

To evaluate system dynamic performance in a weak grid, a small-signal stability analysis of a grid-connected VSC is presented in this section. The three-phase power system involves a converter and its controller, RL filter, connecting line and infinite grid. Assuming an ideal VSC, the VSC local voltage is equal to the controller command, thus it is possible to model the VSC and PWM block by an average voltage

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approach. The system parameters are given in Table I. The augmented model of the VSC and its controller can be developed a s follows.

TABLE I
CONTROLLER PARAMETERS

Parameter	Value (SI units)
VSC maximum power capacity	7 MW
VSC voltage (*L-L* rms)	4160 V
E_{f-ref} (*phase maximum voltage*)	3400 V
K_f	5
K_d	1e5
K_p	0.1
K_v	200
K_{vi}	100
ω_v	500

In other words, in weak grids, acceptable steady-error is achieved at the cost of lower stability margin, thus instability can be yielded during contingencies where load angle swings become large.

IV SIMULATION RESULTS

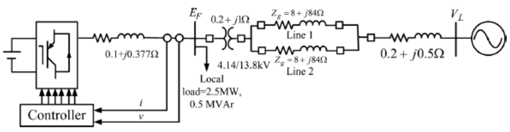

fig- 4. 1simulated system

Fig.4. shows the configuration of the simulated system. The system is composed of a 7.0 MW VSC, filter, local load, transformer and an interface line connecting the VSC to a grid. It is worth to mention that the impedance is the equivalent impedance of the stiff source referred to the distribution level. The simulation study was conducted in MATLAB/SIMULINK environment. The controller parameters are presented in Table I. The DG unit supplies the local load at its output terminal and is connected to a stiff grid through a very weak interface with total impedance of . Since the connecting line is almost inductive, the power capacity of the interface line is approximated by (31) where the notations are defined in Fig.4.1 and is the total reactance of the transformer, line and stiff grid . Therefore, the maximum real power transfer capacity of the connecting line is equal MW. Since the local load power at the rated voltage is 2.5 MW, thus the VSC's maximum power capacity is about 7 MW. The DG works as a PV bus aiming at keeping the filter output voltage constant during grid connection. A wide variety of scenarios have been applied to verify the effectiveness of the proposed hybrid nonlinear controller. System performance at low- and high-power references, transition to islanding, self-synchronization, sudden deviation in grid angle and three phase fault is studied. The advantage of the proposed controller is its flexibility to work in different conditions, i.e., grid-connected and islanded modes without reconfiguration whereas the nonlinear grid synchronizer enables the plug-and-play fig

The following results can be retained from the simulation results: from sections (a) and (b) it is drawn that the controller is able to function in both low-power and high-power levels in very weak grids. The SCR of the system is equal to one and as it will be shown that the VSC can easily inject 0.85 p.u. real power to the grid while it has well-damped transient performance. This is in contrast with conventional vector control which can only exchange 0.6 p.u. real power with a grid; otherwise it might face instability. As will be shown in subsection C, the controller presents very smooth transition to the islanded mode although there is no any islanding detection process and the controller's configuration and parameters are not changed. The self-synchronization ability of the controller will be presented in subsection D where the re-closer is suddenly closed and the VSC is connected to the grid without a pre-synchronization process which is mandatory in conventional controllers. In this case, the supplementary nonlinear controller preserves the self-synchronization capability with large-signal stability. The controller without supplementary nonlinear control cannot offer self-synchronization capability under large-signal disturbances. Fault-ride-thorough is another advantage of the proposed controller and it will be shown that although the VSC

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works as a P-V bus, the current flowing in the power circuit during a three-phase fault is limited because of proper load angle adjustment. Moreover, because of its damping and synchronizing powers, it has the ability to work as a virtual PLL and tracks grid's angle and frequency variation as presented in subsection E.

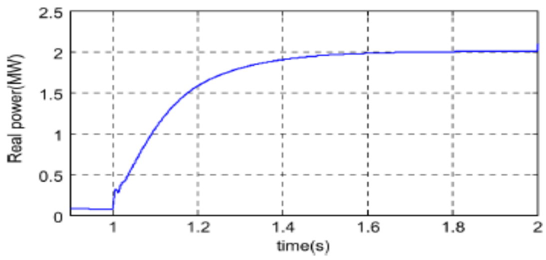

Fig- 4.2. Controller Performance in Low-power injection

Low-Power Injection

To study the behavior of the controller in a wide range of operating points, it assumed that system initially supplies 80 kW, and at , the power reference is increased to 2.0 MW. The real power response is shown in Fig. 4.2, which shows very smooth transition. The rise-time is about 0.6 s and the system yields accurate reference tracking without any overshoot.

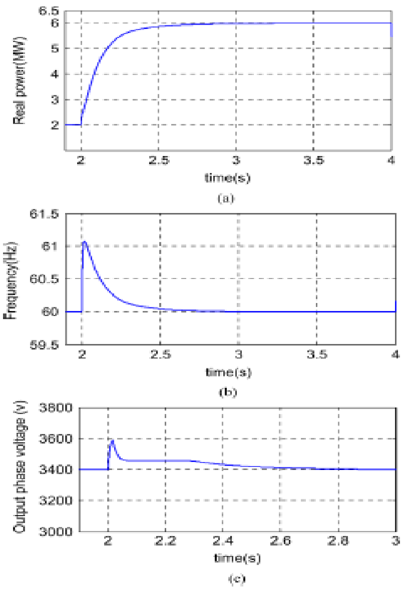

fig. 4.3. controller performance in high-power injection. (a) real power. (b) frequency. (c) phase-voltage amplitude.

B. High-Power Injection With High Load Angles At , the reference power is varied from 2.0 MW to 6.0 MW (0.86 p.u.) which is close to the VSC's maximum power capacity at constant voltage operation and a load angle more than 1.03 rad is expected. Fig. 4.3(a) shows the real power waveform and Fig. 4.3(b) and (c) shows the frequency and phase voltage amplitude variation, respectively. As it is observed, the response is smooth but with larger rise-time; however, it is still stable with damped response and the output power easily reaches 6.0 MW. The output voltage amplitude of the VSC during this transient is shown Fig. 4.3(c) presenting the controller action to boost VSC's voltage during load angle variation to enable high real power injection. This is in contrast with the natural behavior of the system which yields voltage sag subsequent to output power increment and consequently higher voltage drop.

Transition

To Islanded Mode Islanded operation is another scenario that may occur in DG applications to supply local critical loads. At , the VSC is switched to the islanded mode due to a fault in the grid. No controller-mode switching action or reconfiguration is required. The transition is again seamless without any instability

Self-Synchronized Grid

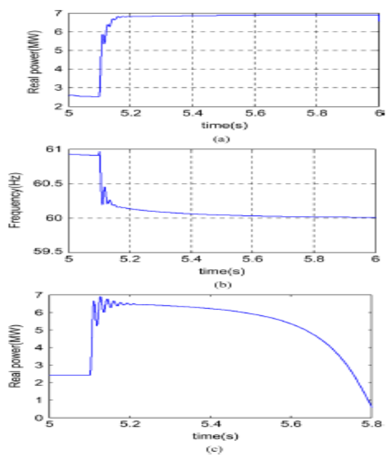

Fig. 4.4 System performance during grid restoration, (a) Real power with nonlinear supplementary controller. (b) Frequency. (c) Real power without the supplementary controller.

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Restoration It is common that a reclose automatically reconnects a DG unit to the main grid after a special time period (usually 1 s). This is due to the fact that most of faults are cleared after few cycles. In this case, connection occurs without synchronization which may lead to severe transients as a result of frequency and angle mismatch of both sides of the reclose at the moment of connection. Weak grids suffer more from the resynchronization transients due to the fact that load angle is inherently large and after grid restoration it may easily move to the nonlinear region and even pass where instability is expected. Fig. 4.4(a) and (b) shows the corresponding waveforms and clearly shows that the system with nonlinear controller provides smooth and fast grid connection. This excellent performance occurs under the fact that there is about 0.9 Hz frequency mismatch between the grid and VSC, and the reference power is equal to 6.8 MW corresponding a the load angle 1.32 rad. The system response without using the supplementary controller is demonstrated in Fig. 4.4(c), which shows that the weak grid conditions cause instability. The current waveform of the system with supplementary control is presented in Fig.4.5, which shows the system well-damped behavior even in the out-of-phase reclosing scenarios, and verifies the plug-and-play feature of the proposed controller.

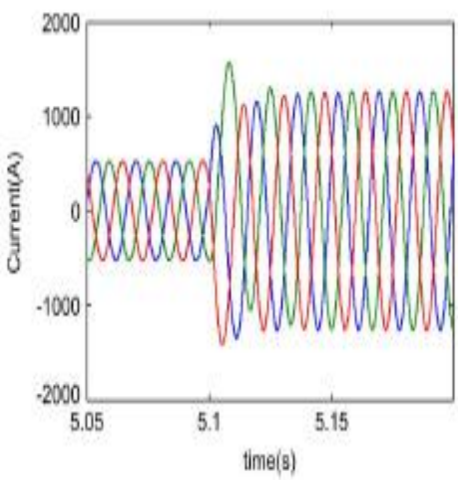

Fig.4.5. Current waveforms subsequent to self-synchronization with supplementary control.

Fault-Ride-Through Capability:

Disturbance in the Grid Angle In addition to the high connecting impedance, weak grids may be characterized by sudden deviations in the voltage angle and frequency. Therefore, it is assumed that at , the power reference is reduced to 4.0 MW, which is not shown here, and at the angle of the grid voltage is abruptly reduced by 0.87 rad. The resulting waveforms of the load angle and phase voltage amplitude are shown in Fig. 4.6 (a) and (b), respectively, which verify that the VSC easily catches the angle deviations even in large disturbances without loss of stability and/or poor performance. It causes an overshoot in the output power and the load angle that is damped within 0.5 s. This is a very potentially interesting feature of the controller where it acts as a virtual PLL, and automatically tracks grid frequency and angle deviations. In this case, as shown in Fig. 4.6 (b), the output voltage amplitude is suddenly reduced to keep the output power limited. This is due to the fact that a lag in the grid voltage angle results in sudden output power increment, thus the output voltage must be reduced to preserve real power stability.

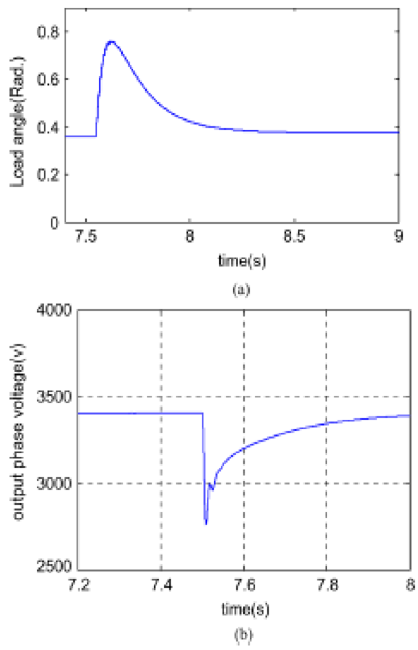

Fig.4.6. Load angle variation subsequent to disturbance in the grid angle.

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4.5 Fault-Ride-Through Capability: Three-Phase

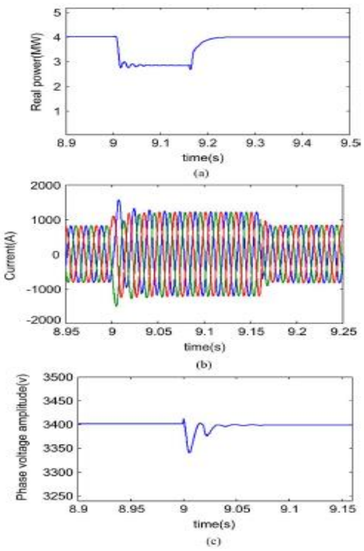

Fig.4.7. System waveforms subsequent to a three-phasefault. (a) Real power.(b) Instantaneous current waveforms.

(c) Amplitude of the phase-voltage.

Fault Fig.4.7. shows the VSC's fault-ride-through performance when a three-phase bolted fault occurs near to the end of connecting line 2. The fault starts at and after 0.16 s, line two is disconnected from the rest of the grid by the protection system. Fig. 3.7(a) shows the real power variation, and reveals that the output real power is limited to 2.9 MW. Note that about 2.5 MW of this power is absorbed by the local load. Fig. 3.7(b) and (c) shows the waveforms of VSC's instantaneous output current and amplitude of the output voltage, respectively. As it is seen, the converter's current is limited to 1420 A which is within the acceptable limits and less than the nominal current; therefore, the VSC is not subjected to over-current during three-phase fault. It should be noted since the VSC acts as a P-V bus, during the fault it aims at keeping the output voltage constant while the current amplitude is limited by proper adjustment of the load angle and inner current limiter. In fact, power damping/synchronization loops aim at limiting the real power and consequently the current flowing in the VSC circuit by proper adjustment of the load angle, whereas the voltage regulation loop tries to keep the local bus voltage constant. The nonlinear supplementary controller also helps the power damping/synchronization loops to undergo the load angle and real power deviations. The real power waveform is smooth and confined during the fault. During the fault, the voltage drops and reactive power increases. At , the breakers of both sides of the connecting line 2 act and the line is decoupled from the rest of the grid. Accordingly, fault is cleared and the line impedance is increased to , which is twice the initial value representing very weak system. This separation event is another large-signal transient occurring in the system. Upon disconnection of line 2 at , voltage, real power and current return to their initial conditions before the fault but in a different operating point since total interfacing impedance is doubled as compared to the pre-fault condition. It should be noted that in these scenarios, the reference real power is kept constant at 4.0 MW. This scenario verifies the robustness of the proposed controller against network system uncertainties because it introduces sudden large variation in total line impedance. It is supposed the fault is cleared at when line 2 is again switched into the circuit.

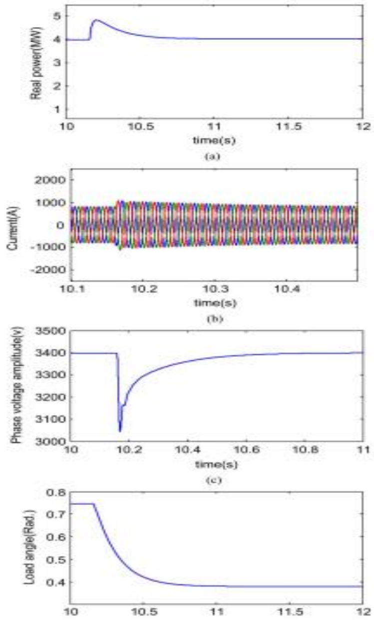

Fig.4.8. System waveforms subsequent to reconnection of line 2. (a) Real power. (b) Instantaneous current. (c) Amplitude of the output phase-voltage. (d) Load angle.

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The corresponding waveforms subsequent to reconnection of line 2, such as real power, current, amplitude of the phase-voltage and load angle are presented in Fig. 4.8. It should be noted that this case is different from the mal-synchronization case presented in subsection C, because only one line is out and system has kept its synchronization with the main grid during all contingencies reported in subsection F. After the recloser of line 2 is activated at , the overall system settles down in less than 0.7s. After reconnection of line 2, the VSC's real power jumps to 4.8 MW, which is due to sudden line impedance reduction but it recovers its steady state value within 0.5 s. The voltage amplitude is reduced during this disturbance to prevent high current and power flow to the line due to immediate line impedance reduction. The reconnection of connecting line 2 is smooth and all the waveforms present well-damped characteristics. Due to proper voltage regulation, the overshoot in the real power and current is very limited although the impedance variation is large. The load angle is reduced from 0.75 rad to 0.38 rad which is equal to its pre-fault value.

V CONCLUSION

In this project, a new control topology is presented to enable effective integration of VSCs to weak grids. The controller has two parts, namely the linear power damping controller and the nonlinear supplementary controller. The linear part mimics SGs with extra power damping-synchronization capability providing self-synchronization with grid which eliminates the need for a PLL. However, in grid restoration scenarios, any large mismatch between VSC and grid frequency and angle may cause poor performance and even instability. These cases are considered as large-signal disturbances, thus the proposed nonlinear controller can enhance system performance in these cases. Moreover, the controller is able to work in very weak grids with SCR and supplies the rated power because of its damping and synchronizing power characteristics. The design process for the linear and nonlinear parts has been presented and numerous simulation scenarios were presented to validate the controller effectiveness.

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