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Integrating Voltage Source Converter to Weak Grids

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***Abstract*— A new control scheme is presented to permit effective integration of voltage source converters (VSCs) in very weak grids. The proposed controller consist of two main parts. The first part is a linear controller that automatically synchronizes a VSC to a grid by providing damping and synchronizing power components, and provides effective full power injection during islanded and grid connected mode. The controller has three cascaded loops namely angle, frequency and power loops for frequency and angle regulation. The angle and frequency loops generate synchronization and damping power components that can track frequency and angle deviations of the grid and automatically synchronizes itself with the grid. Even though the linear controller provides stable and smooth operation in many cases, it cannot guarantee system stability in weak grids where there is sudden large disturbances. To overcome this problem, a supplementary nonlinear controller is developed to support the linear controller and enhance system performance under large-signal disturbances. The controller performance analyzed through MATLAB/SIMULINK software.**

Keywords*— Distributed Generation (DG), Nonlinear control, Power damping,Voltage sourceconverter(VSC),Weak grid.

I. INTRODUCTION

Increasing need for electrical energy under confined availability and supply from conventional energy resources such as fossil fuel has resulted in an energy crisis[1]. The necessity of producing more energy incorporate with the concern in clean technologies contributes in an increased development of power distribution systems using renewable energy resources or distributed generation(DG)[3]. By the development of distributed generation, the depletion of non-renewable sources and its environmental impacts can be compensated and utilize renewable energy sources to meet the demands. Distributed generation (DG) consist of small-scale electric power generators such as gas turbines, fuel cells, solar photovoltaic and wind turbines, that produce electricity at a site close to consumers. The distributed generation has benefits such as lower capital cost, well improved grid asset utilization, reduced transmission and distribution congestion, improved grid reliability, power quality, voltage stability and national security. In grid connected distribution generation systems, voltage source converters(VSC) are the main enabling technology used for interfacing the renewable energy sources to the utility grid[1]. DG has variety of problems during grid interconnection like power quality issues and disturbance from utility grid. The power quality issues may create problems to the industries ranging from malfunctioning of equipments to entire plant shut down. Disturbances from the utility grid including voltage sags and harmonics will disturb the grid connected voltage source converter connected to the grid. Hence proper control of the grid connected voltage source converter is essential for providing a grid with high quality of electric power[4].

The main control topologies of VSC are power angle control, vector control and direct power control. In power angle control, the active power is controlled by the phase angle of the VSC voltage, where as the reactive power is controlled by the magnitude of the voltage of VSC. But the power angle controller have drawbacks such as the controller bandwidth is seriously limited and control system does not provide the capability to limit the current flowing into the converter while the vector control of converter naturally limit the current flowing into the converter during any disruption. The key objective of vector control is to control the instantaneous active and reactive power independently using a fast inner current control loop[5]. Vector current control has no risk of commutation failures in the converter, faster response due to increased switching frequency and minimal environmental impact[4]. Direct power control has several advantages over conventional control techniques such as no precise information of grid voltage is required, no risk of commutation failure and the method works equally well for sinusoidal as well as non-sinusoidal supply voltages.

The advantage of using voltage source converter (VSC) for HVDC applications is its practicability to interface to very weak ac systems, where the conventional thyristor-based HVDC is not suitable. There are several difficulties associated with vector current control of voltage source converter like low-frequency resonance that can interfere with the fast inner current control loop and thus reducing the VSC control performance [5] . A very important and necessary feature of grid side converter control is the grid synchronization. In almost all VSCs connected to ac systems, a phase locked loop(PLL) is used to obtain an accurate synchronization to the ac system. In all these control methods, in order to obtain current and voltage components in synchronously rotating reference frame ,a phase-locked loop (PLL) is essential[3]. However, the investigations have shown that the PLL dynamics might have a negative impact on the performance of voltage source converter in weak ac-system connections. The PLL dynamics adversely affects overall system stability during transients[1],[5]. Beyond the advantages of vector control topology, new control topologies are developed continuously which eliminate the need of phase locked loop (i.e., self-synchronization).One of such technology is power synchronization control, that overcome difficulties associated with vector control of VSCs connected to very weak grids. [1],[5-8] The concept of power synchronization control is similar to power-angle control, i.e using phase angle and voltage magnitude to directly control active power and reactive power but the major difference is that no PLL is needed in power-synchronization control[5].

One of the challenging problem of DG incorporation is the DG connection to very weak grids or high impedance grids. A grid is said to be weak when the flow of active and reactive power into or out of network creates remarkable changes in the voltage magnitude at the point of reference or in the neighboring areas of that point.This problem arises due to high and fast penetration of off-shore wind turbines and remote PV generation units[1],[9-10]. By connecting these renewable energy sources to a weak grid may cause transient over voltages, voltage oscillations, system instability and weak grids experience more difficulty for power flow transfer, thus the maximum quantity of available power that can be injected to the grid is more limited . In order to define the strength of ac systems, the short-circuit capacity ratio (SCR) is proposed .Short circuit ratio defined as ratio of the interconnected grid’s short circuit rating in MVA (before connecting the generator) to the rated dc power. If the SCR<3, then the grid will be weak. The main drawback of vector current control is its limited ability to transfer the rated power in weak grid or high impedance grid. This problem can be eliminated by the concept of power synchronization control[5-8] and is enable rated power transmission to the grid. But this method is incorporated based on small signal dynamics and does not guarantee large signal stability.

Motivated by the aforementioned challenges for the control of VSC, a hybrid nonlinear power damping control of VSCs in weak grids is presented in this paper. The controller consist of a power synchronization loop with an extra cascaded damping and synchronizing loops. The main features of the proposed controller are as follows: 1) Nonlinear power damping controller facilitate self-synchronization of a voltage source converter in weak grids, that is the controller does not requires a separate synchronization unit and it automatically synchronizes itself with the grid. Self-synchronization is a new approach [11], this method needs the initiation time of synchronization and some knowledge from the remote grid, thus it cannot guarantee a true plug-and-play operation. Furthermore, performance and stability of controller in[9] in the case of weak grids have not been investigated. But with this proposed controller the system does not need any initial synchronization with grid and it provides a plug-and-play system.2) The controller has cascaded frequency, angle and power loops. As a result, better stability margin and damping characteristics can be achieved. 3) The controller has a dynamic behaviour like conventional SGs, it can be connected to very weak grids with SCR=1 without compromising the stability. 4) The controller can be used in islanded and grid-connected modes; so there is no need of islanding detection and system reconfiguration. 5) It provides fault clear capability by appropriate adjustment of frequency, load angle and voltage amplitude, and thus limiting current flowing into the interfacing circuit. This proposed non linear control topology can be easily used in VSC-based high-voltage dc (HVDC) transmission systems and DG units; however the main concentration of this paper is on DG applications.

II. PROPOSED LINEAR CONTROLLER SCHEME

This paper emphasis on the evolution of a nonlinear power damping control topology for VSC units in weak grids with applicability in both grid-connected and islanded modes of operation. The schematic diagram of a grid connected VSC supplying a local load is shown in Fig 1. It mainly includes a dc power source, a voltage source inverter (VSI), filter, local loads, and the utility grid.

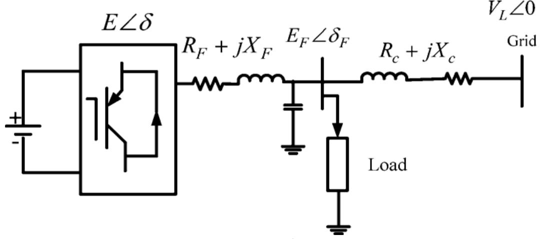


Fig. 1. Circuit diagram of a grid-connected VSC

This paper presents a two-level scheme with cooperative linear and nonlinear controllers. The first level consider the power synchronizing-damping controller and the second level is a nonlinear power damping controller that supports the linear controller to improve system stability in weak grids. In this controller the voltage generation procedure is resemble to a synchronous generator where the voltage, frequency and load angle are tuned by power damping-synchronizing loop, whereas the voltage amplitude is given by voltage controller loop[1]. The VSC’s output real power is controlled by controlling the load angle using the power-damping loop, whereas the reactive power (or alternating voltage) is controlled by controlling the magnitude of the voltage. Since the voltage source converter(VSC) is a voltage-controlled device, an inner current control loop is not essential except during large transients such as faults in the system. During large transients the control strategy should be replaced to current control mode to limit the current amplitude due to faults . In this controller, the synchronization angle for *dq*-frame transformation is attained from the proposed outer-loop controller instead of a phase locked loop(PLL) as shown in Fig. 2. The linear controller scheme has two control concepts; power damping/synchronization damping control and voltage amplitude control.

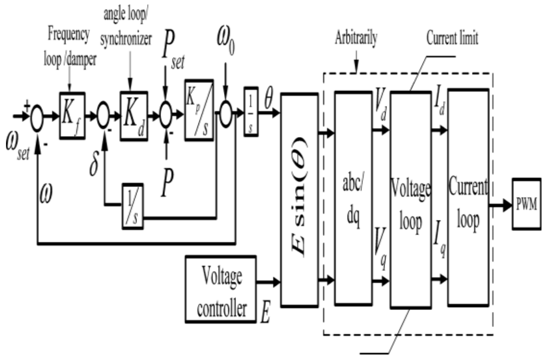


Fig. 2. Proposed linear control scheme

A. Power Damping/synchronization Control

In power damping/synchronization control of a grid-connected VSC , the controller contributes active damping and synchronization power that attenuate power, frequency and load angle oscillations, and thus synchronizes the VSC with the grid during steady-state operation. The basic principle of linear controller scheme is demonstrated in Fig 2. It includes three cascaded loops, namely frequency, angle and power loops. The reference frequency or grid frequency is compared with VSC's frequency and based on the frequency error, the reference of the load angle is obtained. Similarly, the real power reference is determined as a function of the load angle error. Finally, the power synchronization loop adjusts VSC's instantaneous frequency and load angle. The frequency and angle loops generate damping and synchronization power components for the VSC, thus the controller naturally track frequency and angle fluctuation of the grid and automatically synchronizes VSC with the grid. The transferred real power is expressed by the well-known equation

$$P = \frac{E}{R^2+X^2}(XV_L sin\delta + R(E - V_L cos\delta)) \quad ....(1)$$

The strength of electric grid is defined as its ability to maintain its voltage during the injection of real and reactive power. In comparison with stronger system, weaker system will experience large voltage change. The strength of connecting line is depends on short circuit ratio(SCR).The SCR is defined as

$$SCR = \frac{short\ circuit\ capacity}{rated\ dc\ power} \quad ....(2)$$

where the short circuit capacity of the ac system is given by

$$Ssc = \frac{E^2}{Z} \quad ....(3)$$

and Z is the circuit equivalent thevenin impedance. This implies that weaker the grid, the lower the power capacity of the line.

The power-damping control law for a VSC is given as

$$\frac{d\Delta\omega}{dt} = -K_pK_fK_d(\omega - \omega_{set}) - K_pK_f\delta - K_p(P - P_{set}) \ ……(4)$$

The damping and synchronization power components are given by

Damping power =$\Delta P_{damp} = -K_fK_d\Delta\omega$..........(5)

Synchronizing power =$\Delta P_{synch} = -K_d\Delta\delta$ …… (6)

This damping and synchronization powers attenuate frequency and load angle deviation around an equilibrium point and synchronizes the VSC with the grid. In this controller the VSC's frequency and angles are internally available; therefore there is no need of PLL.

B. Voltage Amplitude Controller

The reactive power of a DG unit can be controlled to 1) regulate the terminal voltage (PV bus) or 2) achieve a specific output reactive power (PQ bus). Fig. 3 shows these two different cases. In PV bus control the voltage reference is compared with the actual output voltage. In order to obtain the reference voltage, a proportional-integral (PI) controller is used and that is used for compensating the input error by proper adjustment of VSC's output voltage. Usually it is important to regulate the grid-voltage at the point of common coupling in weak grids, thus PV bus control is the common topology for voltage amplitude control in weak grids .

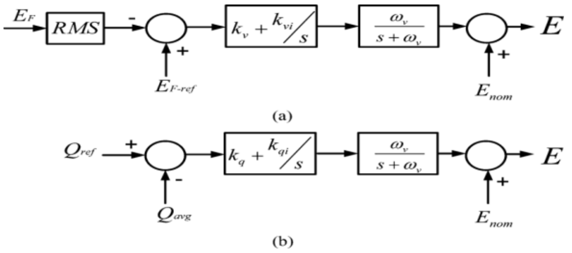


Fig 3.Control topologies for output voltage control.(a)P-V bus control (b)P-Q bus control strategy

Another approach for output voltage control is reactive power regulation as shown in Fig. 3(b). But this is not the common case in weak grids. This is due to the reason that the P-Q control approach significantly degrades stability of DG in weak grids as compared to the P-V control approach. Similar to P-V bus control, a low-pass filter exists after the PI controller. This low-pass filter allows the suppression of voltage oscillations and kept the within acceptable limits.

III. NONLINEAR POWER DAMPING CONTROLLER

The grids with SCR less than 4 is said to be weak and the load angle is usually large .The proposed nonlinear power damping controller can enable higher load angles. However, the linear controller cannot guarantee large-signal stability in all operating conditions. To overcome this problem, a nonlinear power damping controller is proposed and it is supported the linear controller as shown in Fig. 4.

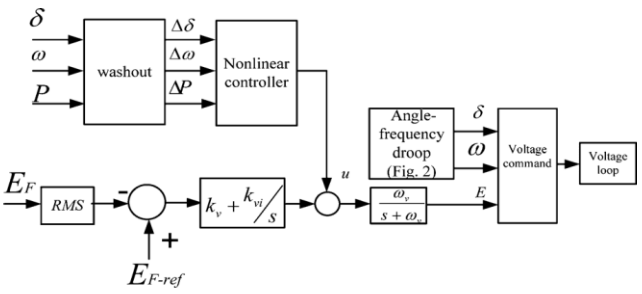


Fig 4.Nonlinear supplementary control scheme

The overall system model is

$$\dot{x}1=x2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$\dot{x}2=a_1x_1+a_2x_2+a_3x_3 \ldots\ldots\ldots\ldots (8)$$

$$\dot{x}3=u_f+E\frac{V_L}{X}x_2cosx_1-\omega_v x_3 \ldots\ldots (9)$$

where $a_1=-K_pK_d$

$a_2=-K_pK_dK_f$

$a_3=-K_p$

$$[x1 \quad x2 \quad x3]=[\Delta\delta \quad \Delta\omega \quad \Delta P]$$

$$u_f=(u\omega_c V_L sinx_1)/X \ldots\ldots\ldots\ldots (10)$$

where u is control input for nonlinear power damping controller.

IV. SIMULATION RESULTS

The configuration of the simulated system in grid connected mode is built by MATLAB/SIMULINK simulation software and shown in fig.5. Table I shows the controller parameters. The system consist of a 7.0 MW voltage source converter, filter, local load, transformer and an interface line connecting the VSC to weak grid. The impedance of 0.2+j0.5 Ω is the equivalent impedance of the stiff source referred to the distribution level. The DG unit will meet the demand of the local load at its output terminal and is connected to a strong grid through a very weak interface of total impedance of│Z│=│R+jX│=│4.4+j43.5│=43.7Ω. The power capacity of the interface line is given by

$$P \approx \frac{E_F V_L}{X}\sin\delta_F$$

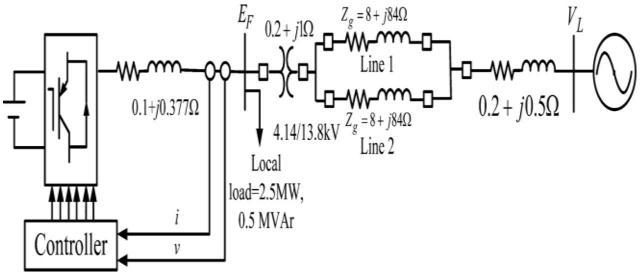


Fig 5.Simulated system of proposed controller

where E_f is the filter voltage, V_L is the magnitude of local load bus voltage, X be the total line reactance i.e is the total reactance of the transformer, transmission line and strong grid (X=42+1+0.5=43.5 Ω).Therefore, the maximum real power transfer capacity of the connecting line is equal Pmax=13880^2/43.5≈ 4.44MW and local load power at the rated voltage is 2.5 MW, thus the VSC's maximum power capacity is about 7 MW.A wide variety of cases have been considered to verify the effectiveness of the proposed hybrid nonlinear power damping controller.

The main peculiarity of the proposed nonlinear power damping controller is its flexibility to work in grid-connected and islanded modes of operation without any reconfiguration. The following observations can be obtained from the simulation results: from sections (A) and (B) it is clear that the controller can function in both low-power and high-power levels in very weak grids and the VSC can easily inject 0.85p.u. of real power to the grid . The controller has smooth and well-damped transient performance. In subsection (C), the controller performance in transition to islanded mode is presented .It has very smooth transition during islanding although there is no any islanding detection process is needed. The controller performance in self-synchronization grid restoration presented in subsection (D)where the breaker is suddenly closed and the VSC is connected to the grid with-out a re-synchronization process which is essential in conventional controllers. Fault-ride-thorough capability is another advantage of the proposed nonlinear controller and it will be depicted in subsection (E) during a three phase fault.

TABLE I
CONTROLLER PARAMETERS

PARAMETERS	Values
VSC maximum power capacity	7MW
VSC voltage(L-L rms)	4160V
Ef-ref(phase maximum voltage)	3400V
K_f	5
K_d	1e5
K_p	0.1
K_v	200
K_{vi}	100
ω_v	500

A. Low-Power Injection

The controller performance in low power injection is shown in Fig 6. It is assumed that the system initially supplies 80 kW, and at t=1 sec, the real power reference is increased to 2 MW. The real power response has very smooth transition and with-out any damping.

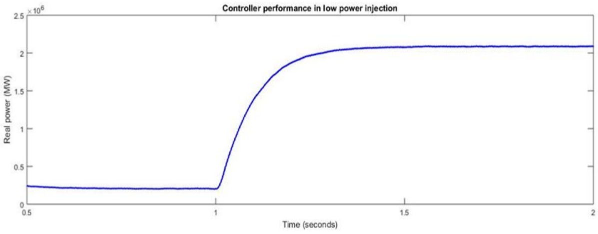
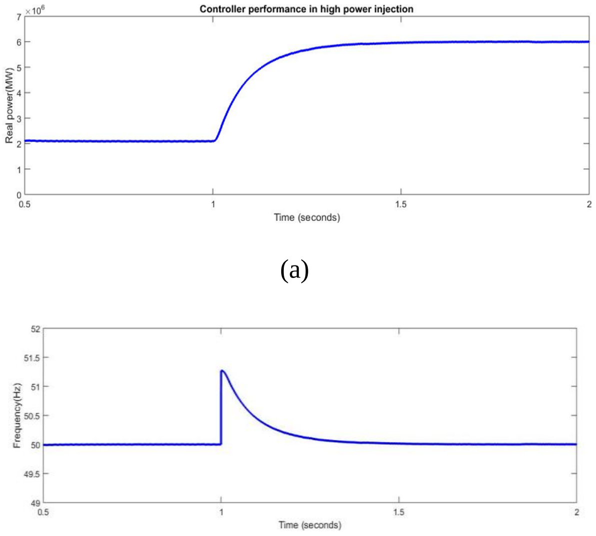


Fig 6.Controller performance in low-power injection

B. High-Power Injection

At t=1 sec, the reference real power is increased from 2 MW to 6 MW(0.86 p.u.) which is close to the VSC's maximum power capacity. Fig. 7(a) shows the real power waveform and Fig. 7(b) shows the frequency during high power injection. As it is observed, the response is smooth ,stable and with-out any overshoot.



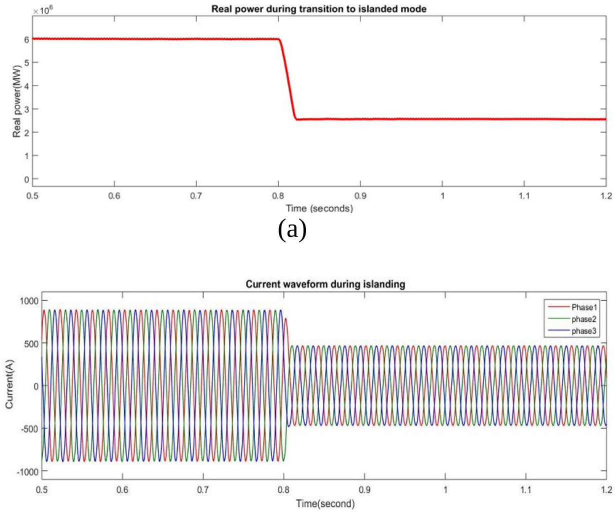
(a)

(b)

Fig 7.Controller performance in high power injection
(a)Real power (b)Frequency

C. Transition to Islanded Mode

DG can be operated in grid connected mode in islanded mode. In grid connected mode DG supplies or draws power to the utility grid. In case of an emergency such as grid maintenance and power shortage during any power interruption the DG shifts to the islanded mode from grid connected mode. In the islanded mode, DG unit will supply local critical loads when the grid is lost keeping the load voltage and frequency within permissible limits. At t=0.8sec, the VSC is switched to the islanded mode from grid connected mode due to a fault in the grid. No controller-mode switching action or reconfiguration is required. The transition to islanded mode is without any instability as shown in Fig. 8. Fig 8(a) shows real power transition and Fig 8(b) shows corresponding current waveform.



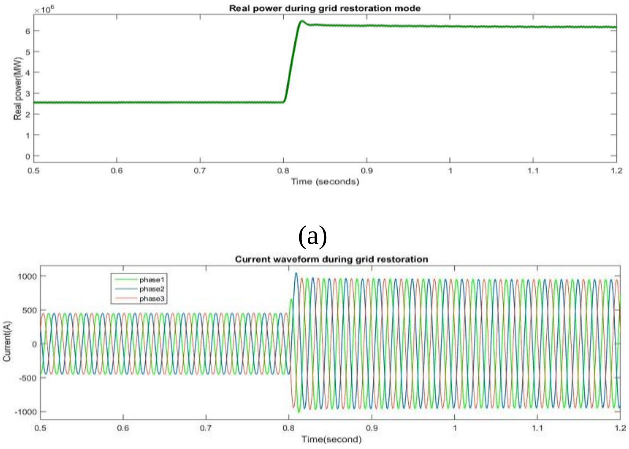
(a)

(b)

Fig 8. Controller performance in islanded mode (a) Real power (b) Current waveform during islanding

D. Self-Synchronized Grid Restoration

It is common that a breaker 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. At t=0.8sec ,the circuit breaker is closed and the VSC is switched to grid restoration mode. In this case, connection of VSC to grid occurs without re-synchronization process. Fig. 9(a) and (b) shows the real power and current waveforms during grid restoration mode. It is clear that the system with nonlinear controller provides smooth and fast grid connection.



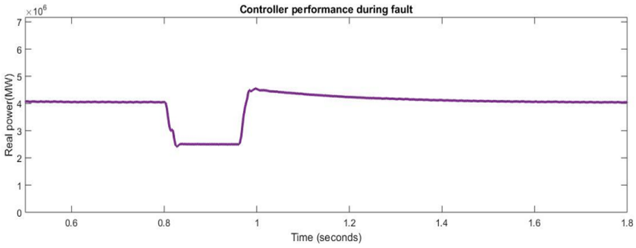
(a)

(b)

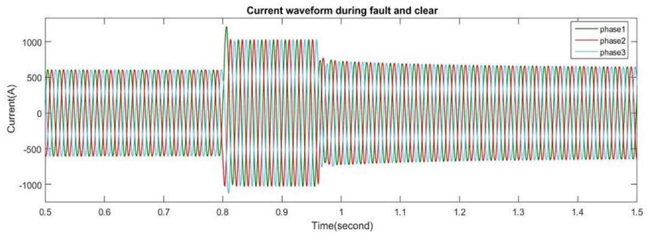
Fig 9.Controller performance in grid restoration mode(a)Real power(b)Current waveform during grid restoration

E. Fault-Ride-Through Capability: Three-Phase Fault

Fig. 10 shows the VSC's fault-ride-through capability when a three-phase fault occurs near to the end of connecting line 2. The fault occurs at t= 0.8sec and after 0.16 sec i.e t=0.96sec, the breakers at the connecting line 2 opens and that disconnect line 2 from the rest of the grid by the protection system. Fig. 10(a) shows the real power variation, (b) shows current waveform. At time t=2 sec, the fault is cleared and the protection system reconnects line 2 to the system and it is shown in Fig 11.



(a)



(b)

Fig 10. Controller performance during three phase fault (a)Real power (b) Current waveform during fault

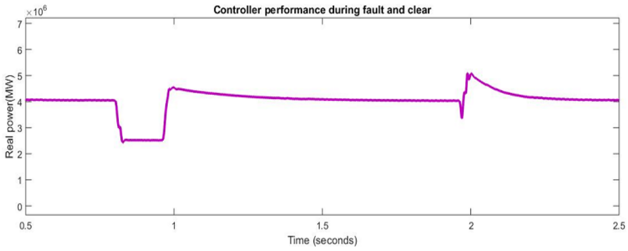


Fig 11. Real power during three phase fault and clear

V. CONCLUSION

This paper presented a new control approach that enable effective integration of voltage source converter to weak grids. The controller consist of two parts, namely the linear controller and the nonlinear power damping controller. The linear part provide damping and synchronizing power that can track frequency and angle deviation and automatically synchronizes VSC to a grid with-out a PLL. The linear controller, in grid restoration mode shows large deviation between VSC and grid frequency and angle and lead to poor performance and even instability. These cases are considered as large-signal disturbances, and can be overcome by the proposed nonlinear controller .The nonlinear controller supports linear controller and enhance system performance during large signal disturbances. Furthermore, the controller can work in very weak grids with SCR<3 and supplies the rated real power with the help of its damping and synchronizing power characteristics. The controller has numerous advantages such as better stability margin, applicable in islanded and grid connected mode and has fault ride through capability.

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