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Design And Analysis Of Vsc's To Weak Grids Using Self Tuned Fuzzy Logic Control

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Abstract
This paper presents a control topology to enable effective integration of voltage source converters (VSC's) in weak grids. The ever increasing progress of high-voltage high-power fully controlled semiconductor technology continues to have a significant impact on the development of advanced power electronic apparatus used to support optimized operations and efficient management of electrical grids, which, in many cases, are fully or partially deregulated networks. Developments advance both the HVDC power transmission and the flexible ac transmission system technologies. The Fuzzy logic controller is developed which effectively reduces disturbances when three phase fault occurs. There is a supplementary nonlinear controller which assists the linear controller and enhances system performance under low power injection in very weak grids and fault-ride-through conditions. The proposed Fuzzy logic controller gives the fast responses even under non-linear characteristics are present. The simulation results are presented by using Matlab/Simulink software and Fuzzy logic tool box.

I. INTRODUCTION
Utility restructuring, technology evolution, public environmental policy, and an enlarging electricity market are allowing the impetus for Distributed Generation to develop into a foremost energy option today. Now-a-days, there is an intensive focus on renewable energy development as a solution to the world's energy needs and to reduce carbon emissions. Many renewable generators are coupled with power electronics, predominantly DC sources such as PV. Integration of DG units to smart grids is a major problem. But VSC's are the better solution for integration of DG units to weak grids.
VSC's are the main technology for integrating the renewable and unblemished energy sources to grids. Vector control and direct power control are the main controlling topologies for VSC. In order to obtain current and voltage in a synchronously rotating reference frame, a phase locked loop (PLL) is needed. But, during transients PLL affects the system stability. To overcome difficulties associated with vector control of VSCs connected to very weak grids, the concept of power synchronization has been presented in and to provide synchronization with grid in steady-state similar to a synchronous generator (SG). But these methods cannot guarantee large signal stability because these are synthesized based on small signal dynamics.
The weak ac grids encounter more problems when connecting DG's. The grid stiffness is a measure of the connecting line capacity to transfer power to a grid. In other words, weak ac grids encounter more difficulty for power flow transfer, thus the maximum amount of available power that can be injected to the grid is more limited. The grid impedance varies according to time as a result of faults and load power variation. The strength of the ac systems is represented by short-circuit capacity ratio(SCR), which is defined as ratio of short circuit capacity to rated dc power. But due to self synchronization concept the VSC's can effectively integrated to weak grids. The grid connected VSC supplying a local load is shown in Fig.1.

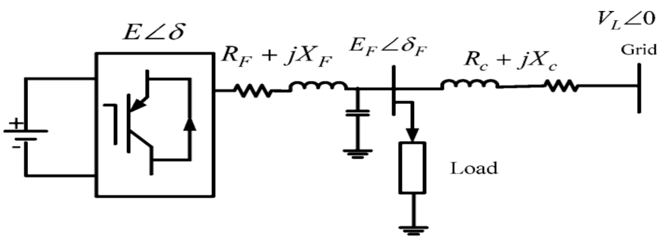

Fig.1. Circuit diagram of a grid-connected VSC.

Here it has two controllers namely linear power-damping/synchronizing controller and supplementary non-linear controller. The linear power-damping and synchronizing controller automatically synchronizes VSC's to weak grids and supplementary non-linear controller will assist the linear controller under non-linear disturbances such as self-synchronization, disturbances in grid frequency and angle, high power injection in very weak grids and fault-ride-through conditions.
Due to power synchronization loop it can be effectively implemented to both grid connected mode and islanded mode. Also, there is no necessary to provide additional

synchronization unit because it has self synchronization capability. Here, a non-linear controller is also provided in order to insure system stability in all operating conditions. The controller has cascaded frequency, angle, and power loops which achieves better stability margin and damping characteristics. Fault-ride through capability can be achieved by proper readjustment of frequency, load angle, and voltage amplitude. Since the controller has a similar dynamic behavior to SG's, it can be connected to very weak grids with SCR=1.
Here PI controller is mainly used to reduce the steady state error. Regarding, the system retaliation and overall stability of the system, it has a negative impact. This controller is customarily used in areas where system's speed is not a matter. Since PI controller has no ability to forecast the future errors of the system it cannot reduce the rise time and eliminate the oscillations. So, Fuzzy logic controller is used in order to get fast response when non-linear conditions occur. The Fuzzy controller is used in power synchronizing loop. Due to Fuzzy logic controller the frequency disturbances are tracked fastly.

II. PROPOSED FUZZY LOGIC CONTROLLER
Fuzzy logic is used to get better results.
The Fuzzy controller consists of following blocks:
- Fuzzification
- Rule base
- Inference engine
- Defuzzification

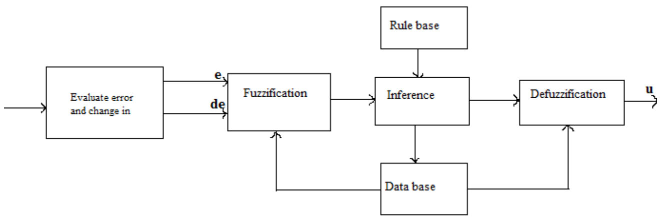

Fig.2.Fuzzy control system

A. Fuzzification Block
This block converts all crisp values into the Fuzzy variables i.e., assigning the membership functions to Input as well as Output Variables. In other words we can call the Fuzzification as the process of assigning the membership functions to input as well as output variables.
Each input and output signals have number of linguistic variables and each linguistic variable is associated with one membership function. The number of linguistic variables varies depending on the application.

B. Rule Base and Inference Engine
Depending upon the problem to be solved, rules are formulated using Input and Output variables and those are stored in Fuzzy rule base. The Fuzzified quantities are then used by inference engine to assess the control rules. That means, the measurements of Input variables of fuzzy controller are properly combined with the relevant fuzzy information rules to make inferences regarding the output variables. Here, rules are formulated using IF AND THEN Rule format.

C. Defuzzification Block
Defuzzification means, the process of conversion of fuzzy values into the crisp values or definite values. That means the result from RULE BASE & FUZZY INFERENCE ENGINE is a fuzzy value which is converted into a single value or crisp value.
In this step, a suitable Defuzzification method is selected for converting each input obtain from the inference engine which is expressed in terms of fuzzy set or fuzzy value. Finally this fuzzy value is converted into the crisp value.
The complete block diagram for fuzzy logic controller is shown in Fig.2.

III. CONTROL STRATEGY
This paper mainly focuses on improvement of non-linear power damping controller to integrate VSC's to weak grids. It has linear power-damping/ synchronizing controller and non-linear power damping controller. Fig.3 shows the linear control structure. Fig.4 shows non-linear control structure. Also, it has a voltage amplitude controller which provides specific control depending on type of bus. It provides different control strategy for output voltage to PV and PQ bus. It is shown in Fig.5. The angle and frequency loops provide synchronizing and damping power components for the VSC to track frequency and angle deviations of the grid and automatically synchronizes with grid. Depending on the frequency error only the reference of the load angle is found and the real power reference is obtained as the function of load angle error. The reference frequency (ω_{set}) in the frequency loop is set equal to the grid frequency and the VSC gives the reference power (P_{set}) in steady state conditions.
The transferred real power is given by

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

SCR defines the strength of the connecting line as

$$\text{SCR} = \frac{short\ circuit\ capacity}{rated\ capacity} \quad (2)$$

Where short circuit capacity (S_{sc}) is given by

$$S_{sc} = \frac{E_0}{Z} \quad (3)$$

Z is the circuit equivalent Thevenin impedance. This implies that the weaker the grid, the lower the power transfer capacity of the line. In a weak grid with, the theoretical maximum power transfer capacity is 1.0 p.u.

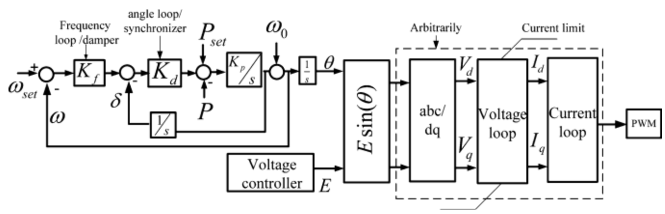

Fig.3.Linear control scheme.

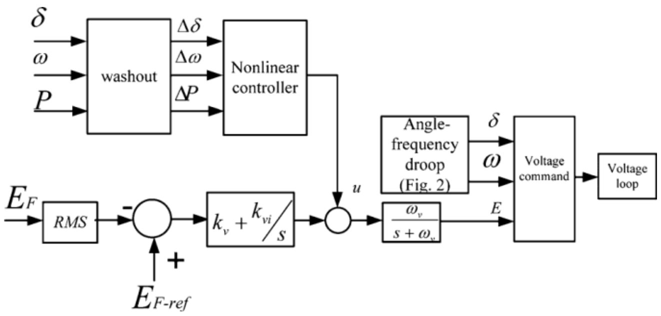

Fig.4.Non-linear supplementary control structure.

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

$$\frac{d\Delta\omega}{dt} = -K_p K_f K_d (\omega-\omega_{set}) - K_p K_f \delta - K_p (P-P_{set}). \quad (4)$$

The damping and synchronization power components are

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

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

It is important to take into account that the VSC's frequency and angle are internally available; therefore, there is no need for a PLL in steady-state operation and several transient conditions.

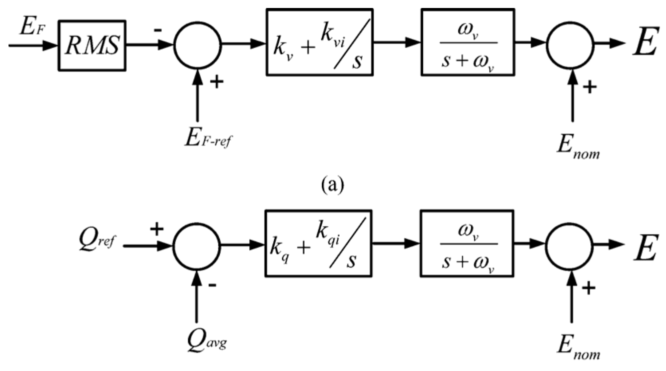

Fig.5. Control topologies for output voltage control. (a) P-V bus control. (b) P-Q bus control strategy.

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

First, the load angle dynamic equation is given by

$$\Delta\dot{\delta} = \Delta w \quad (7)$$

The frequency dynamic equation is expressed by (4) where is given by

$$\Delta P = \frac{\partial P}{\partial \delta}\Delta\delta + \frac{\partial P}{\partial E_F}\Delta E_F \quad (8)$$

The voltage loop dynamic equation is given by

$$\Delta\dot{E} = -w_v \Delta E + w_v \Delta v - w_v K_v \Delta E_F \quad (9)$$

$$\Delta\dot{v} = -K_{vi}\Delta E_F \quad (10)$$

Where v is the output of the integrator K_{vi}, and E_F is the filter voltage amplitude expressed by

$$\Delta E_F = \frac{E_{Fd0}\Delta E_{Fd} + E_{Fq0}\Delta E_{Fq}}{E_{F0}} \pi r^{\cdot 2} \quad (11)$$

$$\Delta E_{Fd} = L_c \frac{d\Delta i_d}{dt} + R_c \Delta i_d - w_0 L_c \Delta i_q \quad (12)$$

$$\Delta E_{Fq} = L_c \frac{d\Delta i_q}{dt} + R_c \Delta i_d + w_0 L_c \Delta i_d \quad (13)$$

The currents dynamics in the dq reference-frame are given by

$$\frac{d\Delta i_d}{dt} = \frac{1}{L}\left(-E_0 sin\delta_0 \Delta\delta + \Delta E\, cos\delta_0 - R\,\Delta i_d + w_0 L_c \Delta i_q\right) \quad (14)$$

$$\frac{d\Delta i_q}{dt} = \frac{1}{L}\left(-E_0 cos\delta_0 \Delta\delta + \Delta E\, sin\delta_0 - R\,\Delta i_q - w_0 L_c \Delta i_d\right) \quad (15)$$

The overall system model is

$$\dot{x_1} = x_2 \quad (16)$$

$$\dot{x}_2 = a_1 x_1 + a_2 x_2 + a_3 x_3 \quad (17)$$

$$\dot{x}_3 = u_f + E\frac{V_L}{X} x_2\, cos x_1 - w_v x_3 \quad (18)$$

Where
$a_1 = -K_p K_d$, $a_2 = -K_p K_f K_d$ and
$a_3 = -K_p$, and $[x_1, x_2, x_3] = [\Delta\delta, \Delta\boldsymbol{\omega}, \Delta P]$. u_f is defined as
$u_f = (u\boldsymbol{\omega}_c V_L \sin x_1)/X$, where u is the control input.

The control objective is to ensure the convergence of the error $e_i = x_i - x_{iref}$ to zero. The first step is to stabilize δ, thus the Lyapunov function

$$V_1 = \frac{1}{2}x_1^2 \quad (19)$$

is defined and the reference of frequency deviation value and $\dot{V}_1$ are given by

$$x_{2ref} = -K_1 x_1\; K_1 > 0 \quad (20)$$

$$\dot{V}_1 = -K_1 x_1^2 + x_1 e_2. \quad (21)$$

In the next step, the Lyapunov function is defined as $V_2 = V_1 + 1/2e_2^2$ and x_{3ref} is chosen to stabilize V_1 and V_2

$$x_{3ref} = c_1 x_1 + c_2 e_2 \quad (22)$$

Where

$$C_1 = \frac{(1-k_1(-a_2+k_1)+a_1)}{a_3} \quad (23)$$

$$C_2 = -\frac{(k_1+k_2+a_2)}{a_3}, k_2 > 0 (24)$$

Finally, by defining

$$V_3 = V_2 + \frac{1}{2}e_3^2 \quad (25)$$

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

and following the approach presented and, it can be shown that the stability of the overall system is confirmed if

$$u_f = \left(A + k_1 \frac{EV_L}{X} cosx_1\right) x_1 \left(B \frac{EV_L}{X} cosx_1 - a_3\right) e_2 + (C - k_3) e_3 \;\; k_3 > 0 (26)$$

Where

$$A = K_f - k_1^2 K_f + k_1 K_d K_f - 2k_1 K_p + \frac{k_1^3}{K_p} - \frac{k_2}{K_p} \quad (27)$$

$$B = (k_1 + k_2 - K_d) K_f + \frac{1-k_1^2-k_2^2-k_1 k_2}{K_p} \quad (28)$$

$$C = -k_1 - k_2 + K_p K_f \quad (29)$$

and $\dot{V}_3$ is simplified to

$$\dot{V}_3 = -k_1 x_1^2 - k_2 e_2^2 - k_3 e_3^2 \quad (30)$$

V. SIMULATION RESULTS

Fig.6 represents the simulated system. It is comprised of a 7.0 MW VSC, filter, local load, transformer and an interface line connecting the VSC to a grid.

The impedance 0.2+j0.5 Ω is the equivalent impedance of the stiff source referred to the distribution level.

The simulation study was conducted in MATLAB/SIMULINK using Fuzzy logic tool box. 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

|Z| = |R+jX| = |4.4+j43.5| = 43.7 Ω.

Considering the connecting line is nearly inductive, the power capacity of the interface line is approximated by

$$P \approx \frac{E_F V_L}{X} sin\delta_F \quad (31)$$

X is the total reactance of the transformer, line and stiff grid (X = 42+1+0.5=43.5 Ω).

Therefore, the maximum real power transfer capacity of the connecting line is equal $P_{max} = 13880^2 / 43.5 \approx 4.44\, Mw$. 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 following results can be obtained from the simulation results.

It shows that the proposed controller effectively works in both low power injection and under three phase fault. 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.

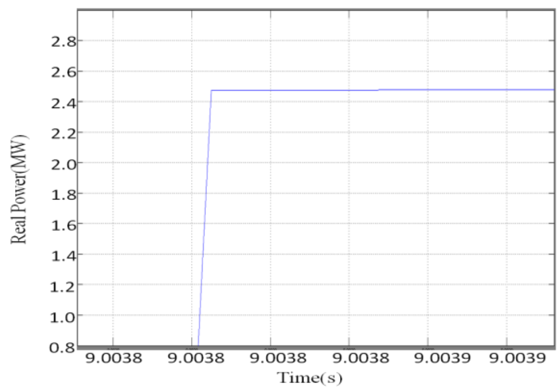

Fig.6. Simulated system.

A. *Low Power Injection*

Here, it is assumed that system initially supplies 0.8 MW, and at t=9s, the power is increased to 2.5 MW. Fig.7 shows the controller performance in low-power injection using Fuzzy Logic controller. It shows that at t=9.0038s, the power is increased to 2.5 MW.

It shows that the Fuzzy Logic controller gives smooth transition. The system gives accurate tracking without any overshoot.

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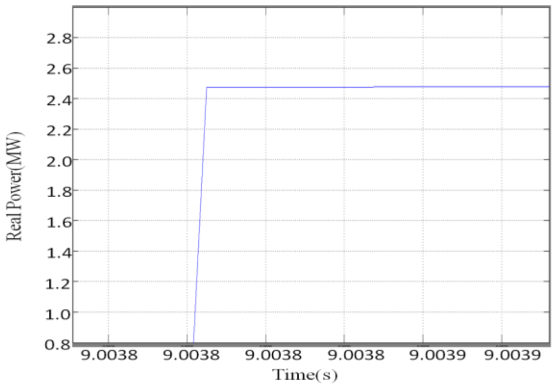
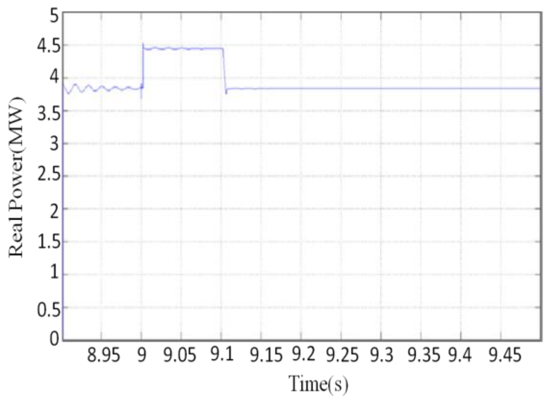
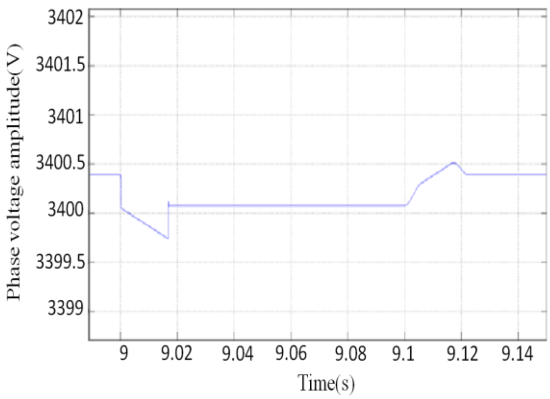


Fig.7 Controller performance in low-power injection using Fuzzy Logic controller

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



(a)



(b)

Fig.8. System waveforms subsequent to a three-phase fault using Fuzzy Logic controller. (a) Real Power. (b) Amplitude of the phase-voltage.

Fig.8 shows the VSC's fault ride through performance when a three-phase bolted fault occurs nearby extremity of connecting line2 using Fuzzy Logic controller The fault starts at t = 9s and line two is disconnected from the rest of the grid by the protection system.

Fig.8 (a) shows the real power waveform subsequent to a three phase fault using Fuzzy Logic controller. It shows that at t = 9.11s the fault is cleared and real power is regulated. Fig.8 (b) shows the amplitude of the phase voltage waveform subsequent to a three phase fault using Fuzzy Logic controller. It shows that at t = 9.122s voltage waveform is regulated.

The Fuzzy Logic controller effectively clears the fault and the regulation of the waveforms is achieved better.

The ripples are also reduced by using Fuzzy Logic controller. The Fuzzy Logic controller gives better performance.

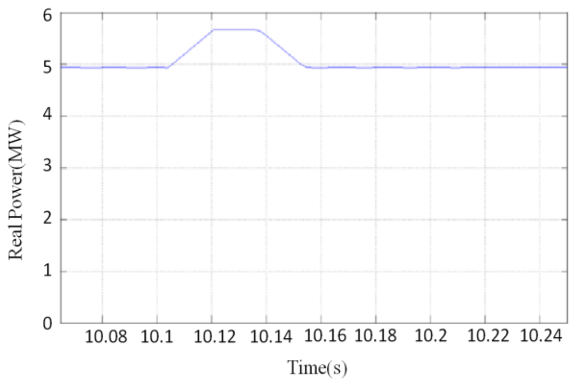


Fig.9 (a) Real Power waveform subsequent to reconnection of line 2 using Fuzzy Logic controller.

Fig.9 (a) shows the real power waveform subsequent to reconnection of line 2 using Fuzzy Logic controller. It shows that from t = 10s the disturbance in real power is started. It is cleared at t = 10.15s and the real power is regulated. There is a fast response in regulating real power.

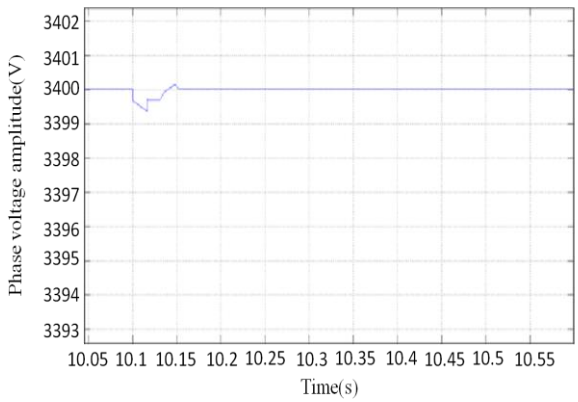


Fig.9 (b) Amplitude of the phase-voltage waveform subsequent to reconnection of line 2 using Fuzzy Logic controller.

Fig.9 (b) shows the amplitude of the phase-voltage waveform subsequent to reconnection of line 2 using Fuzzy Logic controller. After the recloser of line 2 is activated at t = 10.16s, the overall system settles down. The reconnection of

connecting line 2 is smooth and all the waveforms using Fuzzy Logic controller present well-damped characteristics.
Here, it shows the Fuzzy Logic controller gives better performance.

VI. CONCLUSION

In this paper, overall model of grid connected VSC with self synchronization capability is developed. The Fuzzy controller gives the better performance. Due to Fuzzy Logic controller better response is obtained even under non-linear characteristics. The proposed Fuzzy Logic controller works better in weak grid conditions also. The proposed Fuzzy Logic controller is well suited for low power injection and three phase fault conditions in weak grids.

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