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Performance Analysis of a Sliding Mode Control for Distributed Generations

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Abstract – This paper presents the performance analysis of a sliding mode based hybrid controller for three phase voltage source inverter. The main objective of this analysis is to observe the effectiveness of the controller for fault ride through (FRT) capability improvement of the distributed generations (DG). The performance of the conventional PI based cascaded controller is also presented for comparison purpose.

Keywords: Current control, Distributed power generation, Power system faults, PSCAD

1. Introduction

The main driving force for using renewable energy as distributed generation (DG) is its zero carbon emission. In addition to small residential systems, centralized MW class large renewable energy conversion systems are also growing very fast over the last decade. Apart from the environmental benefits, grid connected distributed generation systems have a number of impacts on the existing power systems either in a positive or negative ways. Installation of distributed generations can reduce the transmission line loading and losses incurred for this. This is due to the fact that less amount of power needs to be transferred through the transmission lines from the conventional power plants as some load demand will be served by the DGs at the distribution level. It can also delay the up-gradation of transformers and transmission lines, and reduce the frequency of their maintenance works [1]. However, transmissions lines are, in general, highly efficient and major power losses occur in the distribution networks. Increase of power flow in distribution network can increase the overall power loss of the system. Therefore, addition of DGs may increase the overall line losses unless their locations are chosen carefully depending on the load conditions [2]. They can provide a good support during peak power demand and thus electricity generation from DGs can also be cost effective. The installation of DGs can improve the voltage profile at the point of common coupling (PCC) and oscillatory stability of the power systems [3]- [4].

However, the major concern of using grid interfaced distributed system is its intermittency. This reduces the reliability of the overall system. Alternatively, the penetration level of PV plants has to be sufficiently low to maintain the same reliability of operations. Besides, integration of DGs can introduce power quality problems like flicker, voltage dips, harmonic distortion, etc.

The impact of distributed generation to the power system is becoming significant fast due to the increase of grid connected applications of alternative energy sources. Because of higher penetration to the grid, the requirement of providing dynamic grid support by these renewable energy sources is becoming important. For example, grid connected PV plants must remain connected to the power system during the fault conditions, as per recent German grid codes [5]-[6]. This means the DGs need to ride through the fault. Fault ride through (FRT) requirement has already been implemented in many countries for wind energy systems. This means that the plants must be able to

- Remain connected to the network during grid faults;
- Provide dynamic voltage support by delivering reactive power;
- Recover the reactive power delivery fast to the steady-state value after the fault is cleared.

The limiting curves for type 2 generators (plants other than synchronous generators) are shown in Fig. 1 [5]. When the terminal voltage drops down to 0 pu, the plant can only be disconnected from the network if the duration of this voltage level persists for more than 150 ms. The recovery

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of the voltage has to be fast enough during the post fault condition that the terminal voltage recovers 90% of its nominal value within 1.5s.

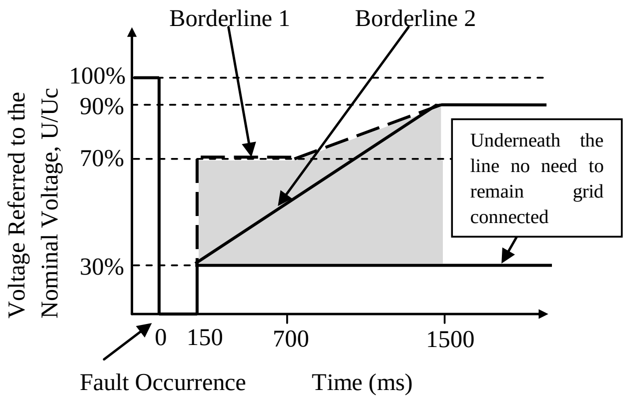

Fig. 1. Limiting curves of type-2 generator terminal voltage [5]

Hence, for the fault ride through requirement of the grid connected DG system the major challenge is its grid side inverter control; the inverter must have fast transient response to regulate the DC link voltage, under and overvoltage protection, and fast terminal voltage recovery capability if there is any fault in the system. Conventional PI controllers [7]-[9] exhibit slow response as the controllers are unable to handle the nonlinear nature of the system. In modern control systems for power electronics, sliding mode control (SMC) has started to draw attention because of its large disturbance rejection capability and robustness. This paper presents a comparative analysis of the performance of a sliding based inverter connected to distribute generations with a focus on the fault ride through (FRT).

2. Grid Integration of DG

The application of power conditioning units (PCU) can be classified into two categories. Input side converters are generally used to control the DG to operate in the maximum power point. Grid side converters, on the other hand, generally control the real and reactive power delivery to the grid by regulating DC link voltage and grid side terminal voltage respectively. Fig. 2 shows the grid integrated DG system which has been used for this study. In this system a 5 MW plant is connected to the DC side of the three phase voltage source inverter. The AC side of the inverter is connected to the double circuit transmission line via a step up transformer. The parameters for the system are given in Table 1.

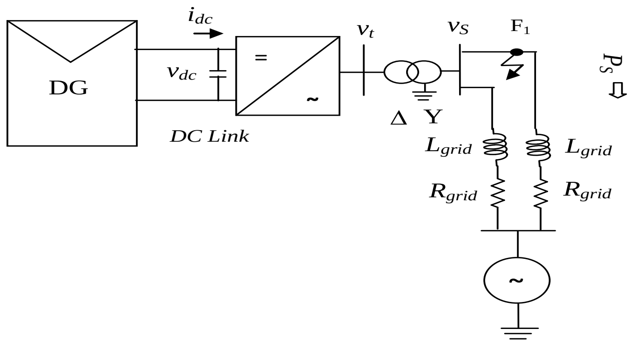

Fig. 2. System structure of grid integrated DG

Table 1. Line parameters

V_{dc}	1.2 kV
Transformer voltage ratio (Δ-Y)	0.763 kV/ 22 KV
R_{grid} (for each line)	9.68 Ω
L_{grid} (for each line)	0.18487 H

3. Control of Voltage Source Inverter

The control of voltage source inverter is generally twofold. The outer loops control the real and reactive powers by controlling DC link voltage and grid side terminal voltage respectively, and generate the reference currents for the inner loops. The inner loops regulate the grid side currents to track the reference values so that required real and reactive powers are delivered successfully to the grid.

3.1 Outer Loop Control

Fig. 3 shows the three phase view of the grid connected inverter. Let us suppose, the grid side d and q axis voltages and currents are v_{sd}, i_d and v_{sq}, i_q respectively. The equations for grid side real and reactive power in space phasor form are given by:

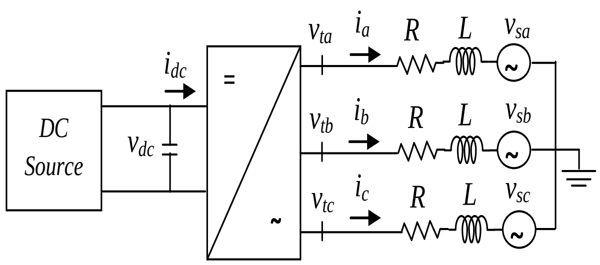

Fig. 3. Grid connected voltage source inverter; 3-phase view

$$P_s = \frac{3}{2}(v_{sd} i_d + v_{sq} i_q) \quad (1)$$

$$Q_s = \frac{3}{2}(-v_{sd} i_q + v_{sq} i_d) \quad (2)$$

Using phase lock loop (PLL), v_{sq} is set to zero. Hence (1) and (2) reduce to:

$$P_s = \frac{3}{2} v_{sd} i_d \quad (3)$$
$$Q_s = -\frac{3}{2} v_{sd} i_q \quad (4)$$

Let us suppose transformer resistance and inductance are R and L respectively. R is very small compared to L. Hence, power loss across R is generally ignored. Ignoring the switching losses, the following relationship can be found during steady state:

$$P_{dc} \approx P_t \approx P_s = P \quad (5)$$

Again from dc side:

$$P_{dc} = v_{dc} i_{dc} \quad (6)$$

Therefore, from (3), (5), and (6), it can be stated that reference current for d-axis (i_d^*) can be obtained by controlling the DC link voltage. Reactive power transfer Q_S is directly proportional to the terminal voltage V_S. Hence from (4), the reference current for q-axis (i_q^*) can be found by regulating terminal voltage V_S.

a) Conventional PI based cascaded control

As mentioned above, the i_d^* and i_q^* can be generated by regulating DC link voltage and grid side terminal voltage. Therefore, in conventional PI based inverter control, the following equations are used for the outer control loops:

$$i_d^* = (K_{P\_Vdc} + \frac{K_{I\_Vdc}}{s})(v_{dc}^* - v_{dc}) \quad (7)$$
$$i_q^* = (K_{P\_VS} + \frac{K_{I\_VS}}{s})(v_S^* - v_S) \quad (8)$$

where K_{P_Vdc}, K_{I_Vdc}, and K_{P_VS}, K_{I_VS} are the gains of the PI controllers; v_{dc}^* and v_S^* are reference DC link voltage and reference grid side voltage respectively

b) Sliding mode based hybrid control

For the sliding mode based hybrid control, the following first-order sliding surfaces are considered for the outer control loops [10]:

$$S_{Vdc} = e_{vdc} + K_{Vdc} \frac{de_{vdc}}{dt} \quad (9)$$
$$S_{VS} = e_{vs} + K_{VS} \frac{de_{vs}}{dt} \quad (10)$$

where $e_{Vdc} = v_{dc}^* - v_{dc}$ and $e_{VS} = |v_S^*| - |v_S|$. K_{Vdc} and K_{VS} are sliding surface coefficients. d and q axis reference currents are generated using the following two equations [11]:

$$i_d^* = e_{Vdc}\left(K_{P\_Vdc} + \frac{K_{I\_Vdc}}{s}\right) + |S_{Vdc}|.K_{S\_Vdc}.sgn(S_{Vdc}) \quad (11)$$
$$i_q^* = e_{VS}\left(K_{P\_VS} + \frac{K_{I\_VS}}{s}\right) + |S_{VS}|.K_{S\_VS}.sgn(S_{VS}) \quad (12)$$

where K_{P_Vdc}, K_{I_Vdc}, K_{P_VS}, K_{I_VS}, K_{S_Vdc}, and K_{S_VS} are the controller gains. The sliding mode controllers help to reject large voltage disturbances. The sliding surface magnitudes are also used as adaptive gains. They provide large gains fast during grid faults for voltage recovery. They also reduce the chattering problem because of the smaller gains during the steady state. The PI controllers control the settling time and overshoot to some extent.

3.2 Inner Loop Control

a) Conventional PI based cascaded control

The block diagram of PI based conventional controller for three phase voltage source inverter is shown in Fig. 4 [12]. The outer loops generate the reference currents using (7) and (8). In the inner loop the error signals of the d and q axis currents are progressed through PI controller to generate the reference voltage in d-q axis. They are transformed from d-q axis to abc axis and are given to the comparator block to generate gate pulses for the IGBTs.

b) Sliding mode based hybrid control

The control block for sliding mode based hybrid control is shown in Fig. 5. The outer loops are designed based on (11) and (12). The inner loop control design is described below.

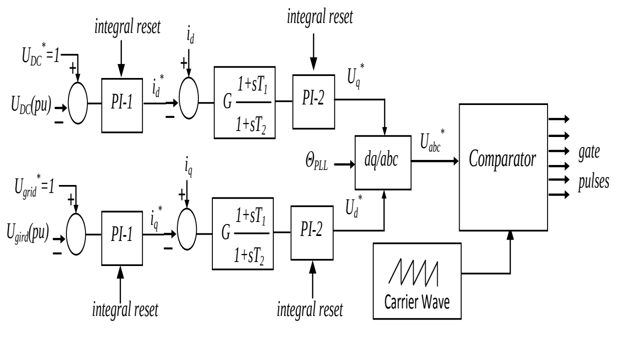

Fig. 4. PI based cascaded control

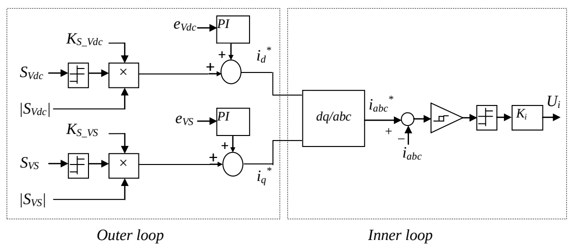

Fig. 5. Sliding mode based hybrid control

From Fig. 3 the following state space equations can be found:

$$L\frac{di_a}{dt} = -Ri_a + v_{ta} - v_{sa} \tag{13}$$

$$L\frac{di_b}{dt} = -Ri_b + v_{tb} - v_{sb} \tag{14}$$

$$L\frac{di_c}{dt} = -Ri_c + v_{tc} - v_{sc} \tag{15}$$

Voltage drop across the resistance is very small and generally ignored. When the upper switch is conducting and the lower switch is off, for each leg the following relationship can be obtained:

$$L\frac{di_i}{dt} = \frac{1}{2}v_{dc} - v_{si} > 0,\ i = a,\ b,\ c \tag{16}$$

Similarly when the upper switch is off and lower switch is conducting:

$$L\frac{di_i}{dt} = -\frac{1}{2}v_{dc} - v_{si} < 0,\ i = a,\ b,\ c \tag{17}$$

From (16) and (17) it is clear that the current slope is positive when $v_t = v_{dc}/2$ and negative for $v_t = -v_{dc}/2$. Therefore, the following sliding mode control laws are considered:

$$v_{ti} = K_i sign(S_i)\frac{v_{dc}}{2},\ i = a,\ b,\ c \tag{18}$$

where $S_i = i_i^* - i_i$; this implies:

$$L\frac{di_i}{dt} = K_i sign(S_i)\frac{v_{dc}}{2} - v_{si} > 0,\ i = a,\ b,\ c \tag{19}$$

$$\dot{S}_i = \frac{di_i^*}{dt} - K_i sign(S_i)\frac{v_{dc}}{2L} + \frac{v_{si}}{L},\ i = a,\ b,\ c \tag{20}$$

The reaching condition for the sliding surface is $S_i S^{\cdot}_{\ i} < 0$. Therefore, the value of K_i should be:

$$K_i > 2\left[L\frac{di_i^*}{dt} + v_{si}\right]/v_{dc},\ i = a,\ b,\ c \tag{21}$$

The switching laws are defined as follows:
$U_i > 0$; Upper switch is On and lower switch is Off.
$U_i < 0$; Upper switch is Off and lower switch is On .

where $U_i = K_i sign(S_i)$. A hysteresis buffer is also used to limit the switching frequency and avoid the chattering problem. The controller gains are shown in Table 2.

4. Simulation results

The comparative analysis between the conventional PI control and the proposed sliding mode based hybrid control for dynamic as well as transient performances is performed in this study. The simulations are performed using PSCAD/EMTDC. The dynamic responses of the controllers are shown in Fig. 6. In this figure the power generation from the DG has been varied in steps with time. From the graph of the terminal voltage, it can be observed that it has oscillations during the power variations for the conventional PI controller. On the other hand, the terminal voltage variation is much less for sliding mode based hybrid control than the former. In the response of DC link voltage, there is a significant improvement in the dynamic performance for sliding mode based hybrid control.

Table 2. Controller Gains

PI based cascaded control			
PI-1	*P* = 14	*I* = 0.35	
PI-2	*P* = 0.001	*I* = 0.0002	
Sliding mode based hybrid control			
$K_{P\_Vdc} = 0.2$	$K_{I\_Vdc} = 0.25$	$K_{P\_VS} = 1.2$	$K_{I\_VS} = 0.12$
$K_{Vdc} = 0.001$	$K_{VS} = 0.001$	$K_{S\_Vdc} = 50$	$K_{S\_VS} = 0.05$

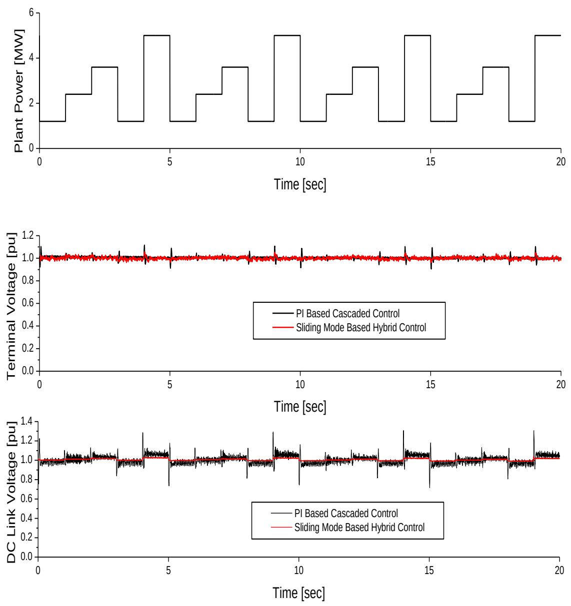

Fig. 6. Dynamic Performance

The transient analysis is done to study the effectiveness of the sliding mode based hybrid controller for the fault ride through of the distributed generations and compare it with that of the PI controller. For transient analysis, different symmetrical and unsymmetrical faults are considered at F1 location on one of the double circuit transmission lines as shown in Fig. 2. It is assumed that the fault occurs at 0.1 s and the breakers open at 0.25 s. Therefore, duration of the fault in the network is 0.15 s; this is the maximum time of fault for which the DG needs to remain connected to the grid. The fault is cleared at 0.3 s and the breakers reclosed at 0.8 s.

Figs. 7 and 8 show the responses of grid side terminal voltage and DC link voltage respectively for 3LG fault for the two controllers. Integral controller reset is considered during the fault for both control methods to avoid the voltage overshoots. The grid side voltage recovery after the breaker operation is very fast in both cases of the two controllers. But there are more oscillations in case of the PI controller.

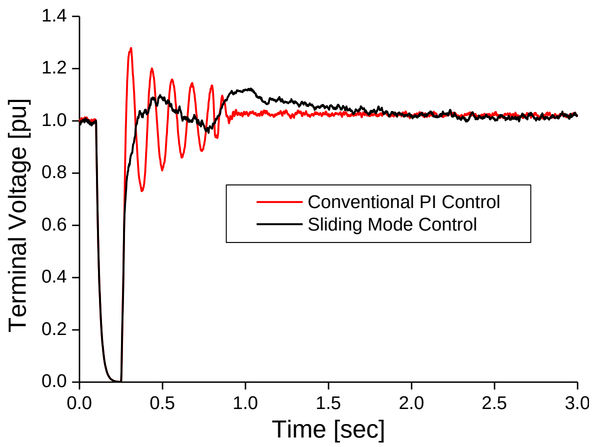

Fig. 7. Grid side terminal voltage (3LG fault)

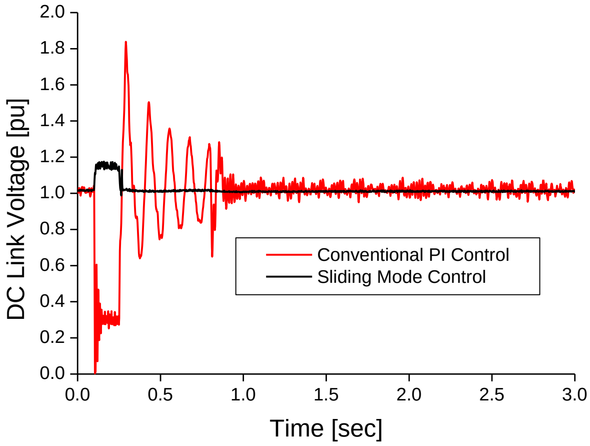

Fig. 8. DC link voltage (3LG fault)

For DC link voltage, more improved performance can be achieved by the proposed sliding mode based hybrid control compared to the PI controller. A dip appears in the DC link voltage in the case of the PI controller, which may lead to the shutdown of the system and also lead to a violation of the requirements of fault ride through. Also there is large voltage overshoot in the DC link voltage in the case of the PI controller, which can damage the devices unless any protection circuit is not used. Whereas the DC link voltage overshoot in the case of the sliding mode controller is less than 1.2 pu and it recovers to 1 pu immediately after the breaker operation to isolate the fault.

The phase current (*Ia*) with its reference value (*Ia**) for the sliding mode based hybrid controller are shown in Fig. 9. The figure shows the phase current for steady-state, during the fault and after the fault. It can be seen that the phase current can successfully track its reference value in all the conditions. Therefore, good responses can be achieved for the terminal voltage and DC link voltage as shown in Figs. 7 and 8.

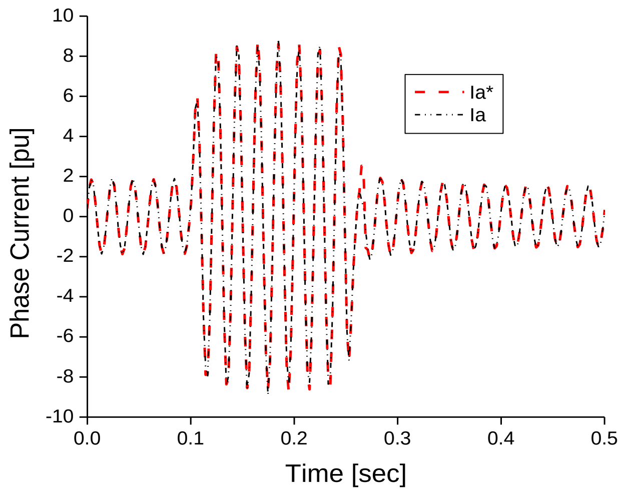

Fig. 9. Phase-a Current

Similarly, responses of the grid side terminal voltage and DC link voltage for 2LG, 1LG, and LL faults in the case of the sliding mode based hybrid controller are shown in Figs. 10 and 11 respectively. For all types of fault, the system can recover the terminal voltage successfully and there are very little overshoots. The DC link voltage overshoots are also limited within 1.1 pu.

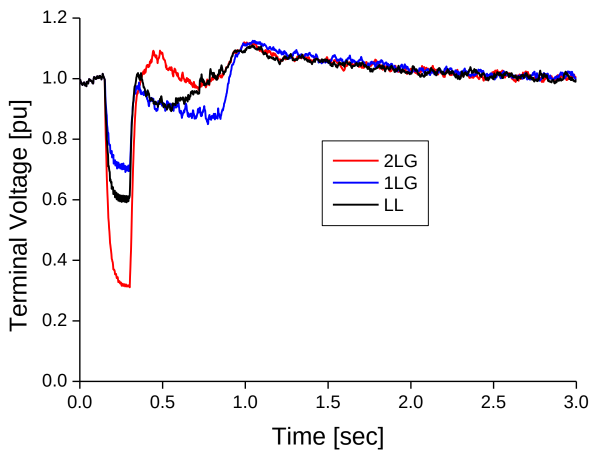

Fig. 10. Grid side terminal voltage

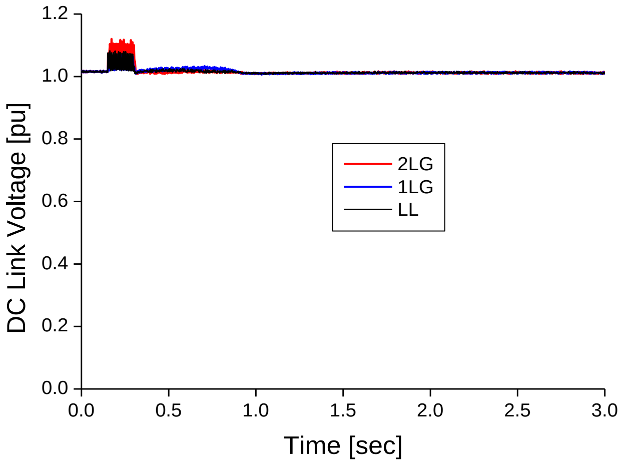

Fig. 11. DC link voltage

5. Conclusion

In this paper, a sliding mode based hybrid inverter control has been proposed. The performance of the controller is compared with that of a conventional PI controller. It has been found that the sliding mode based hybrid controller has much better current tracking capability, and gives more improved terminal voltage and DC link voltage during grid faults compared with that of a conventional PI controller. Hence, it can be concluded that the sliding mode based hybrid controller gives improved dynamic as well as transient performances for grid connected distributed generations.

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