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A novel control strategy for power conditioning unit to enhance power quality during FRT

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Abstract

This paper proposes a novel control strategy for power conditioning unit (PCU) to enhance power quality during fault ride through (FRT) operation. During unsymmetrical fault condition, PCU injects sinusoidal currents by adopting control method suggested. By using effective current limitation technique suggested here, injected currents can be limited to their rated value during a fault. To avoid triggering of overcurrent protection, FRT operation is ensured. In case of failure of dc-dc unit to handle the maximum PV power, a non-maximum power point tracking (Non-MPPT) operation mode is proposed to get it operated under severe fault condition.

Keywords: DC link voltage control, power conditioning unit, current limitation, fault ride through

1. Introduction

Due to latest achievements in renewable energy technologies, FRT capability plays an important role, for grid interconnection. FRT research on photovoltaic (PV) power conditioning unit is lagging behind wind power generation [1]-[4]. FRT capability of PV system not only influences grid stability, but also restores the healthiness of grid. Hence it is a challenge for grid interconnection of PV system, which affects PV power generation utilization. Different techniques have been studied [5]-[7], analysed for enhancing FRT capability of PV systems.

A single phase grid connected PV system for FRT capability was illustrated [8], for controlling both active and reactive powers [9]. FRT brings grid connection benefits and it also solves difficulties in design of PCUs. At the moment of grid fault, overvoltage and overcurrent conditions are occurred [10]-[13]. A curve between % voltage sag and operation time is as shown in Fig.1 w.r.t. E.ON code for FRT, used in various studies of FRT capability [14]-[20]. Area above red curve illustrates that PV system remain grid connected. Shaded area below red curve demonstrates that, PV system will be tripped for safety purposes.

As an example, PCU must remain grid connected for 1.5 seconds for 90% voltage sag. PV system has capacity that should give a linearly proportional active/reactive current output for the period of 90% to 50% voltage sag, according to E.ON code. At 50% line voltage drop, distributed generator should output 100% reactive current. Fig.2 illustrates need to support PV network during grid fault [21]-[22].

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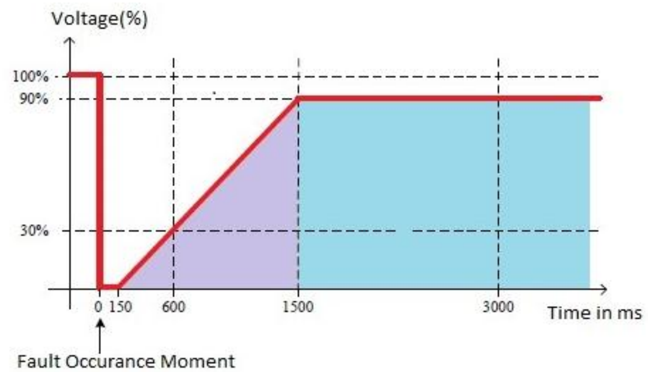


Fig. 1 % Voltage sag Vs operation time curve.

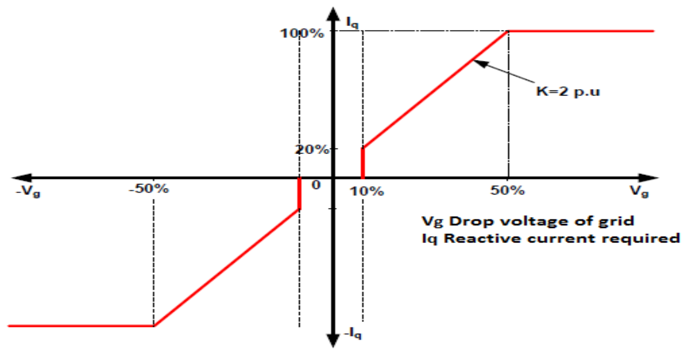


Fig. 2 Necessity to support voltage of PV network at the moment of grid fault.

This paper suggests decrease in dc link ripples during unsymmetrical faults with dc-dc converter control. The impacts of PV arrays on whole network are significantly examined and proposed a control strategy for PCU during FRT [23]-[28]. In addition, it also proposes (i) control method to take out double grid frequency oscillations from injected real power and dc link voltage; (ii) Non-MPPT operation mode for dc-dc converter during fault, when converter unable to handle maximum PV power; (iii) current limitation technique to limit injected currents to their rated values.

The paper is organized as: Section II explains the proposed control strategy which includes two stage three phase grid connected PCU operation, current limitation technique and control diagrams with flowchart. Simulation results are discussed in section III. Section IV concludes the paper.

2. Proposed Control Strategy for Power Conditioning Unit

Let us discuss about a novel control strategy for PCU unit in order to enhance power quality during FRT. A two stage three phase grid connected PCU is considered for studies.

2.1 Grid connected PCU

A two stage three phase grid connected PCU is demonstrated in Fig. 3, containing boost converter and PCU interconnected through dc link capacitor. There is no negative sequence (NS) in voltages and currents at the moment of fault during the balanced voltage sag. In a general case, all real power produced by PV panels is conveyed to dc link. This active power from PCU injected into grid. The active power supplied by PCU is not as much as power injected to dc link. That increases the dc link voltage. Injected active power has double grid frequency oscillations. These oscillations of dc link voltage have a negative effect on life cycle of capacitive dc link. In next section, a novel control technique to decrease such oscillations is suggested.

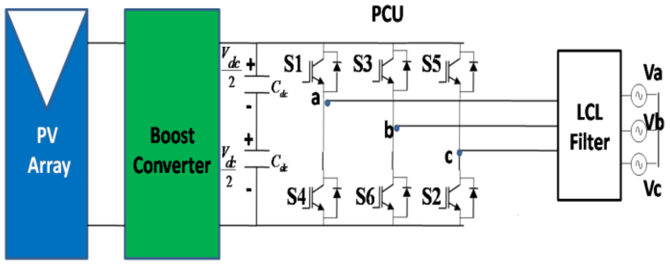


Fig.3 Grid connected PCU.

2.2 Current limitation technique

An effective current limitation technique is suggested to control overcurrent failure. When voltage sag takes place, rated power of converter must be refreshed. This is called as new nominal power (NNP). At the moment of voltage sag fault condition, value of NNP is not equal to nominal power of converter which depends on depth of voltage sag. Hence NNP can be calculated as

$$NNP = \frac{\sqrt{V_p} - \sqrt{V_n}}{V_{base}} S \tag{1}$$

Where S is apparent power of converter, V_{base} is base voltage, which is equal to root mean square value of line to line grid voltage. Subtraction of $\sqrt{V_p}$ and $\sqrt{V_n}$ makes a constant term. Some important parameters are: $V_p = \left(V_\alpha^{+2} + V_\beta^{+2}\right)$ and $V_n = \left(V_\alpha^{-2} + V_\beta^{-2}\right)$, V_α, V_β, i_α, i_β are voltages and currents in stationary reference frame (SRF). V^+, V^-, I^+, I^- are amplitudes of positive and negative sequences of grid voltage and current. Reduction in phase voltages will decrease NNP. Hence, according to depth of voltage sag, reactive power can be calculated as follows:

$$\begin{cases} Q = 0 & if \;\; V_{pu} > 0.9 \\ Q = S \text{ x } 1.5 \text{ x } (0.9 - V_{pu}) & if \;\; 0.2 < V_{pu} < 0.9 \\ Q = 1.05 \text{ x } S & if \;\; V_{pu} < 0.2 \end{cases} \tag{2}$$

V_{pu} can be calculated as

$$V_{pu} = \frac{\sqrt{v_\alpha^2 + v_\beta^2}}{v_b} \tag{3}$$

V_b is grid voltage in natural reference frame. By knowing NNP and reactive power Q, maximum active power (P_{max}) for PCU to inject to grid far away from overcurrent can be calculated as:

$$P_{max} = \sqrt{NNP^2 - Q^2} \tag{4}$$

For the converter operation under deep voltage sags, NNP will be low, as $\sqrt{V_p} - \sqrt{V_n}$ becomes small. Therefore, during deep voltage sag, we can write condition:

$$if\,(Q = NNP) \rightarrow Q = NNP, and \;\; P_{max} = 0 \tag{5}$$

In case NNP is less than reactive power reference, converter cannot inject reactive power to grid. When voltage sag is observed, NNP and Q can be calculated with the help of equations (1) and (2). Active power (P_{max}) is controlled with the help of equation (4). During voltage sag faults, dc link controller continuously compares P_{max} and active power reference (P^*). At $P_{max} > P^*$, active power the converter injected earlier can still be supplied.

Then again, if $P_{max} < P^*$, PCU cannot inject P^* computed by dc link controller. In order to keep dc link voltage steady, PV exhibits to separate maximum power from PV array. This mode is called Non-MPPT operation mode. It is in operation when fault takes place and $P_{max} < P^*$. Fig. 4 explains how dc-dc converter is regulated in Non-MPPT mode. Right hand side (RHS) of Fig. 4 is selected for Non-MPPT mode, as slope is higher; working point can move quicker than left side. To move to right side, duty cycle is decreased with the help of equation (6).

$$V_{PV} = (1 - D)V_{dc} \tag{6}$$

Where V_{dc} is dc link voltage and V_{PV} is PV voltage. When fault occurs, Non-MPPT mode comes into operation and duty cycle calculation is made by using equation (7).

$$D_c = \frac{P_{\max}}{P_{MPP}} D_{MPP} \tag{7}$$

Where D_c is approximate value of duty cycle. D_{MPP} and P_{MPP} are duty cycle and PV power respectively at MPP.

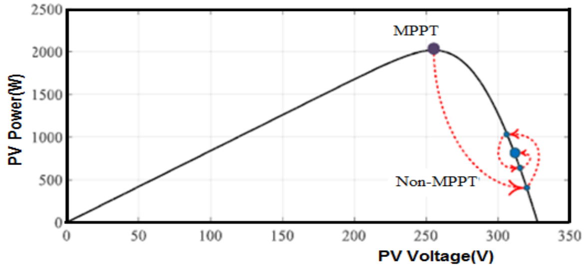


Fig. 4 P-V Characteristics of PV Array.

2.3 Control Diagram with Flowchart

The proposed control diagram is as shown in Fig.5, which comprises of two stages, dc-dc converter and PCU. PI controller is controls dc voltage. The output of PI controller decides active power reference to set dc link voltage. Two Proportional-Resonant (PR) controllers control injected currents separately. DC-DC converter works as MPPT. DC-DC converter shifts to Non-MPPT mode during fault in grid and PCU cannot handle maximum power of PV. Fig. 6 shows flowchart for proposed control technique. In case V_{pu} falls beneath 0.9 for every unit, voltage sag detection block will produce fault signal which is then used to activate NNP, Q, and P_{max} blocks. For examination amongst P_{max} and P^*, an error signal is produced.

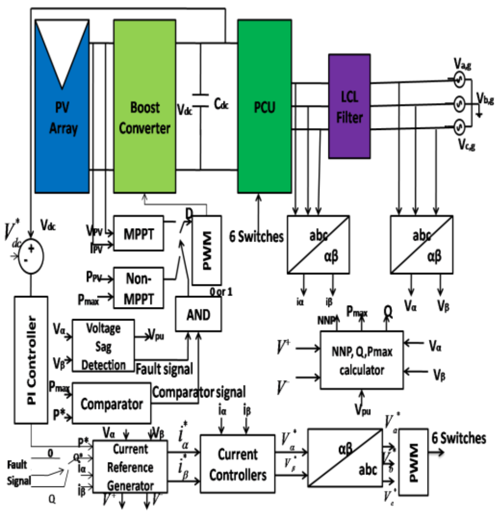


Fig.5 Control diagram.

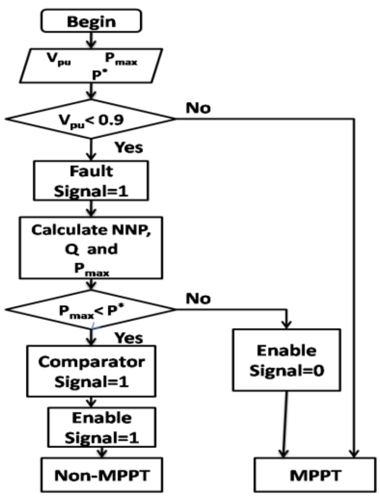


Fig. 6 Flowchart.

DC-DC converter control is as shown in Fig. 7. Red dashed line represents calculation for Non-MPPT control, which is activated when Enable Signal is equivalent to 1. D_c can be calculated with the help of equation (7). In AND block of Fig. 7, if signals of comparator and fault are equivalent to 1, dc-dc converter changes to Non-MPPT mode. For Non-MPPT operation, PI controller will have to tune to a new duty cycle. PCU operation under various grid conditions is covered in Table 1. MPPT keeps working under severe condition when fault takes place in network and $P_{max} < P^*$. It shows that PCU has ability to inject P_{max} of PV array and additionally required reactive power. For this situation, fault signal is 1, while comparator signal is zero.

Table 1. Operation of PCU during Various Grid Conditions

Grid Condition	FRT	DC-DC Converter Operation
$V_{pu} > 0.9$	Disabled	MPPT
$V_{pu} < 0.9$	$P_{max} > P^*$ Enabled	MPPT
	$P_{max} < P^*$ Enabled	Non-MPPT

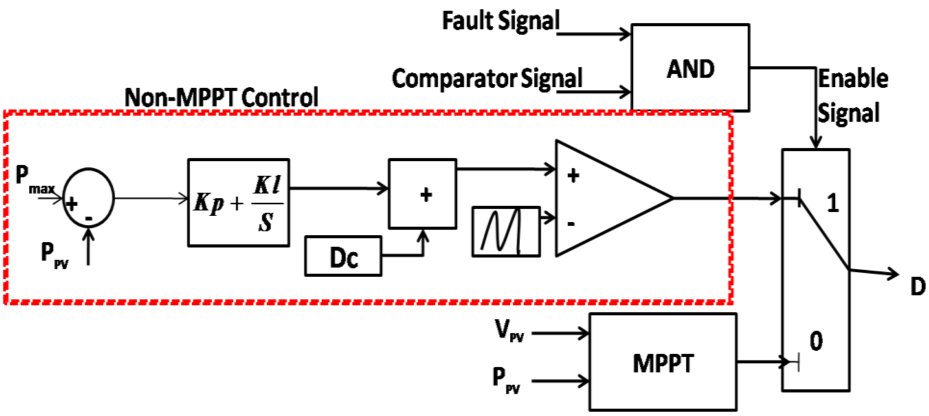
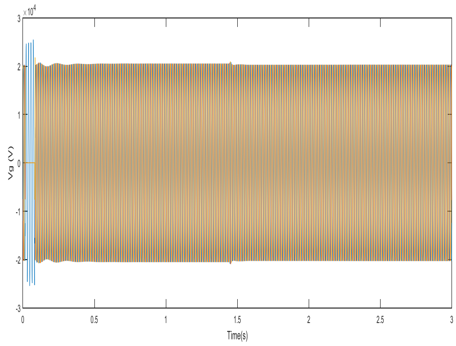


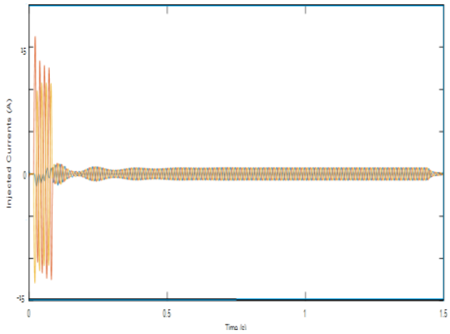
Fig. 7 DC-DC converter control diagram.

3. Simulation Results

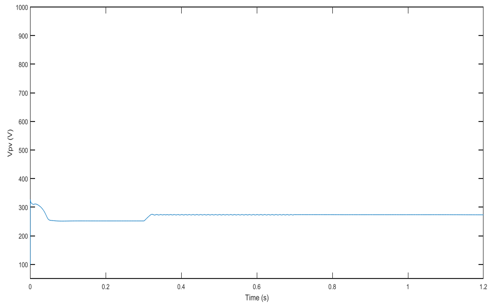
To study proposed strategy, a proposed model is developed in Matlab/Simulink. DC link voltage is assumed to be 500 V. A case is studied, in which double line-ground fault is occurred in phase B and C and ground at t = 0.2 sec. Three phase grid voltages are shown in Fig. 8 (a). When unsymmetrical fault happens, FRT operation is empowered. Fig. 8(b) shows injected currents during fault, which are controlled by utilizing control technique. As voltage sag is not within the prescribed limits of definition inconformity with IEEE 1159 standard, there is increment in currents in Phase B and Phase C. Injected currents are sinusoidal. PV voltage is as appeared in Fig. 8(c). Fig. 9(a) shows injected active and reactive powers, at the moment of fault. When unbalanced voltage sag observes, active power suddenly falls to prevent failure in overcurrent. Injected reactive power increases once fault signal is equal to 1 and oscillates with frequency, as explained in proposed method and shown in Fig. 9(a). Fig. 9(b) shows dc link voltage, decreased at the moment of fault. Modulation index is shown in Fig. 9(c). Fig. 9(b) demonstrates that dc link voltage is settled appropriately.



(a)

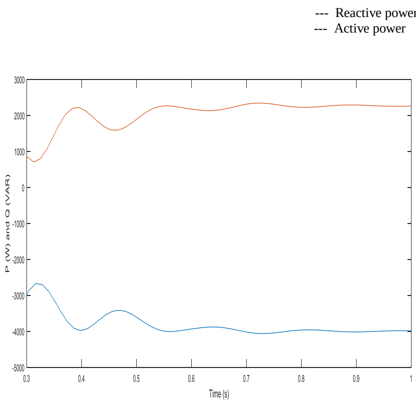


(b)

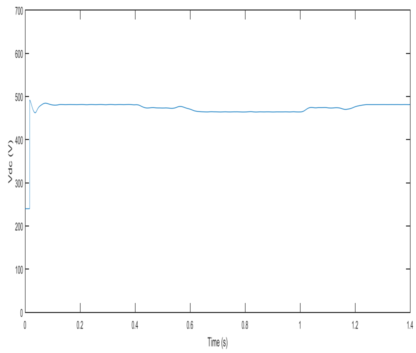


(c)

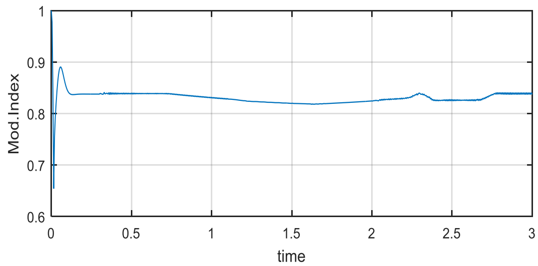
Fig. 8 PV system simulation results for: (a) three phase grid voltages,(b) three phase currents,(c) PV voltage, at the moment of unsymmetrical fault.



(a)



(b)



(c)

Fig. 9 PV system simulation results for: a) active and reactive powers (b) dc link voltage at the moment of unsymmetrical fault (c) modulation index.

4. Conclusion

A novel control strategy for PCU to enhance power quality during FRT is proposed in this paper. Control strategy suggested here explains two operation modes, MPPT and Non-MPPT mode; both can work in severe fault conditions. One of significant contribution of this paper is Non-MPPT operation mode for dc-dc converter. This operation mode is examined in this paper.

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