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Active and Reactive Power Priority Imposed by Current Limit Logic in Inverter-based Generators

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SUMMARY

There is an increased demand for renewable energy sources (RES) around world partly due to governments' response to environmental concerns and improving economics of the underlying technology. As a result, the total generation capacity of RES installed globally doubled between 2009 and 2018. The most rapidly increasing type of RES are solar photovoltaic (PV), wind farms and battery energy storage systems (BESS) [1].

RES that are connected to the grid through power electronic inverters are called inverter-based generators (IBGs). Inverters transform the output voltage of RES into an appropriate AC network voltage and frequency. With the high penetration of IBGs in today's grid, the dynamic performance of the technology needs to be modeled accurately to represent the characteristics of the inverters. Western Electricity Coordinating Council (WECC) has released generic models for RES modeling which include generator, electrical and power-plant control models [2].

The control structure of the IBGs is hierarchical. The highest level is plant-level controller, also referred to as outer loop, which controls the active and reactive power output of the IBGs. The electrical controller controls each individual inverter and forms the inverter level or inner loop control. The electrical control model receives the input commands from the plant-level controller and adjusts the active and reactive power output of the inverter. It checks the active and reactive current commands with current limit logic before sending them to the generator model [3].

Through the current limit logic in electrical control model, each command is subject to the respective current limit, 0 to I_{pmax} for active current and I_{qmin} to I_{qmax} for reactive current. Then, the total current of $\sqrt{Ipcmd^2 + Iqcmd^2}$ is limited by I_{max} of the inverter. In situations where current limit I_{max} of the inverter is reached, the user should specify whether active or reactive current takes precedence, which is called active power (P) or reactive power (Q) priority modes. If the inverter plant is set under P-priority, the current limiter will limit reactive current to prioritize active current injection within the defined I_{max} capability, while under Q-priority mode, the current limiter will limit the active current to prioritize reactive current injection within the defined I_{max} capability.

This P- or Q-priority operating mode becomes more critical during a severe network disturbance in which the voltage at the Point of Interconnection (POI) drops significantly. The

active or reactive power output from the inverters could increase rapidly and reach the active or reactive power limits ($I_{pmax,}$ I_{qmin} or I_{qmax}) due to large voltage variations during post-fault period. This could lead to a different power transfer and system stability issues. Furthermore, if momentary cessation is employed, the inverter has to re-start injection of current after partial voltage recovery and current controls take over. The current control can be vital during voltage recovery since the network may already be in a vulnerable state immediately following the disturbance. An improper current logic limiter setting can further delay the system recovering to a stable equilibrium point or may cause system collapse.

In the WECC second generation generic model, different electrical controllers have been developed for PV, wind and BESS, i.e., REEC_A, REEC_B and REEC_C. In these models, based on *P*- or *Q*-priority mode, the current limit logic block sets active and reactive current commands throughout simulations.

In this paper, different test cases are simulated demonstrating the results in P- or Q-priority modes and the associated issues with each of these modes are presented. Then, potential mitigations are tested and the results are discussed.

KEYWORDS

Renewable energy sources (RES), inverter-based generators (IBG), WECC second generation models, current limit logic, active and reactive power priority

1. INTRODUCTION

Penetration of renewable energy sources (RES) into the modern distribution and transmission power grid continues to increase around the world. RES that are connected to the power grid using power electronic inverters are called inverter-based generators (IBGs). Inverters transform the output voltage from RES into the appropriate AC network voltage and frequency.

The control structure of the IBGs is hierarchical. The highest level is plant-level controller also referred to as an outer loop which controls the active and reactive power output of the solar plant or wind farm. The electrical controller controls each individual inverter and forms the inverter level or inner loop control. The electrical controller receives the input signals from the plant-level controller and adjusts the active and reactive power output of the inverter [4].

Different control modes have been defined for the IBGs reactive power control module in both plant level and inverter level. In the case of plant-level control, the reactive power flowing in a designated branch is measured and the reactive power output from each inverter is adjusted in a coordinated manner. Therefore, the controller should coordinate between multiple inverters enhancing the voltage control capability.

The plant-level control module may include any or all of the following reactive power control modes:

- Closed-loop voltage regulation (V control) at a designated bus with optional line drop compensation, droop response and dead band.
- Closed-loop reactive power flow regulation (Q control) on a user-designated branch, with optional dead band.

Further discussions on different control modes and normal or abnormal performance categories of IBGs can be found in Cigré Technical Brochure 727 and IEEE Standard 1547-2018.

In some operating scenarios, an IBG should generate power up to its maximum active and reactive power capability. For instance, when a contingency occurs in the local network, the IBG should contribute in recovering the voltage magnitudes to a normal condition by supplying or absorbing reactive power. In the inverter-level controller of the plant, the maximum current passing through each inverter is limited and the summation of the active and reactive currents should not go beyond the maximum current rating. If under a critical condition, the injected current exceeds the maximum current limit, the inverter controller will curtail active or reactive current based on the provided settings. Therefore, a current limit logic has been implemented to different IBG models and the planning engineer can set it up to provide priority to active (or reactive) current and let the model curtail the reactive (or active) current. To set up the current limit logic, the engineer should consider the inverter's active and reactive power capability in addition to the network configurations in the area nearby to point of interconnection (POI). Otherwise, issues might occur during the operation, such as IBG's active power curtailment or abnormal post-fault operating conditions.

In this paper, we will show the different responses of inverters under P- or Q-priority modes and I_{max} capability. The results will be thoroughly investigated and compared with each other and the advantages and disadvantages of different settings will be explained. The tests will be performed for several network conditions including both weak networks with low short circuit ratio (SCR) at the POI and strong network with high SCR at the POI. It is expected that this paper provides the reader with a clear understanding of limitations of P- and Q-priority modes imposed by current logic limiter in different network conditions.

2. DYNAMIC MODEL STRUCTURE AND SETTINGS

Currently, in North America, the second generation of generic WECC models are commonly used to simulate the dynamic response of IBGs with aggregated capacity of 20 MVA or higher and connected to the transmission system (60 kV and above). Different models have been developed for solar plants, type 3 and 4 wind turbines as well as battery energy storage systems. The second generation of generic renewable energy systems models consists, at this time, of a library of ten models, i.e., REGC_A, REEC_A, REEC_B, REEC_C, REPC_A, WTGT_A, WTGAR_A, WTGPT_A, WTGTRQ_A and WT1P_B [1].

An inverter-based plant model is shown in Fig. 1. As it shown, the model is composed of three different modules as follows [2]:

a) *regc_a* – which is the renewable energy generator/converter model and has inputs of real (*Ipcmd*) and reactive (*Iqcmd*) current command and outputs of real (*Ip*) and reactive (*Iq*) current injection into the grid model.
b) *reec_a* – which is the renewable energy electrical controls model a, and has inputs of real power reference (*Pref*) that can be externally controlled, reactive power

reference (*Qref*) that can be externally controlled and feedback of the reactive power generated (*Qgen*). The outputs of this model are the real (*Ipcmd*) and reactive (*Iqcmd*) current command.

c) *repc_a* – which is the power plant controller (PPC) model *a*. This model has inputs of either voltage reference (*Vref*) and measured/regulated voltage (*Vreg*) at the plant level, or reactive power reference (*Qref*) and measured (*Qgen*) at the plant level. The output of the *repc_a* model is a reactive power command that connects to *Qref* to the *reec_a* model.

A current limit logic has been implemented in the inverter-level control model. The purpose of the current limit logic is to allow the plant to properly allocate its current capacity upon reaching to the maximum current capability of the inverter. Priority is given to either the active or reactive current command depending on the value of the current limit logic priority flag (**pqflag**). The first priority command is bounded only by the current rating of the converter. Hence, the second priority command is bounded by whatever capacity is leftover after generating the first priority command.

The electrical control module first determines the active and reactive current commands independently according to the active power control option and reactive power control option. Each command is subject to the respective current limit, 0 to I_{pmax} for active current and I_{qmin} to I_{qmax} for reactive current. Then the total current of $\sqrt{Ipcmd^2 + Iqcmd^2}$ is limited by I_{max}. In situations where current limit I_{max} of the equivalent inverter is reached, the user should specify whether active or reactive current takes precedence, by setting the pqflag parameter in the inverter-level control module.

In addition to the current limit logic, voltage-dependent current limits have been incorporated into the inverter-level controller to control the current injection based on the terminal voltage level. The voltage-dependent current limits (VDL) curves (VDL1 and VDL2) are used to model limits of both active and reactive current injection, respectively, when the voltage is within the indicated value.

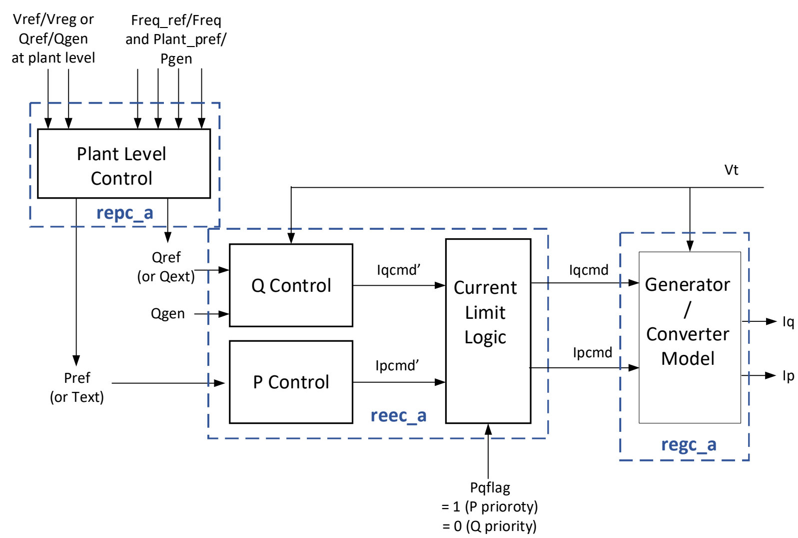

Fig. 1. Generic WECC PV plant model [2]

The following equations represent the logic of Q- or P-priority in the current logic limit module:

- If the electrical control module is under Q-priority (with pqflag = 0)

$$Iqmax = \min\{\mathrm{VDL1}, Imax\} \tag{1}$$

$$Iqmin = -1 \times Iqmax \tag{2}$$

$$Ipmax = \min\{\mathrm{VDL2}, \sqrt{Imax^2 - Iqcmd^2}\} \tag{3}$$

$$Ipmin = 0 \tag{4}$$

- If the electrical control module is under P-priority (with pqflag = 1)

$$Iqmax = \min\{\mathrm{VDL1}, \sqrt{Imax^2 - Ipcmd^2}\} \tag{5}$$

$$Iqmin = -1 \times Iqmax \tag{6}$$

$$Ipmax = \min\{\mathrm{VDL2}, Imax\} \tag{7}$$

$$Ipmin = 0 \tag{8}$$

3. SIMULATION TEST AND RESULTS

A sample solar power plant was selected to simulate the tests in this paper. The power plant has a total active power capability of 99.6 MW, reactive power capability of ± 15.5 MVAr with Mbase of 100.8 MVA. Considering the loss in generator step-up transformers (GSU), collector system equivalent, main transformer and the attachment line, the power plant will have a maximum active power injection of 98.32 MW at the POI. The diagram of the solar power plant model in the test case is shown in Fig. 2.

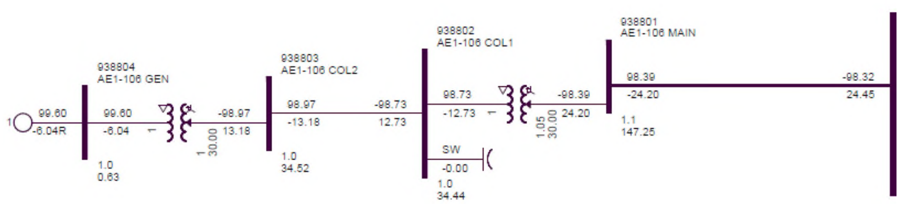

Fig. 2. The diagram of the solar power plant model in PSS/E

Initially, the solar power plant has been set up to control the POI with “Plant level V control + local coordinated V/Q control” mode.

The Fig. 3-9 show the response of the solar power plant after applying contingency at the POI at 1 second with duration of 9 cycles. The figures are mainly focused on the active power and reactive power injection for the purpose of understanding current control logic after the fault.

Fig. 3 shows the test results for a three-phase fault at the POI in the system with high SCR, while the current limit logic module is under Q-priority. In this test, the active power of the solar power plant does not recover back to its pre-fault value in the simulation because the maximum active power is limited by I_{max} value as shown in the equation (3). The active power of the solar power plant is prioritized by changing the control module to P-priority. Subsequently, the active power recovers back to its pre-fault value without limitation from reactive power injection as demonstrated in Fig. 4. However, the system under the low SCR, the active power of the solar power plant may not recover back to its pre-fault condition even under P-priority mode as explained through the following examples.

Fig. 5 shows the response of the same solar power plant when a three-phase fault is applied at the POI in the system with low SCR. The active power does not recover back to its pre-fault value. The active current injection I_{pcmd} is limited to a value less than 1 p.u. by the lower inverter terminal voltage during the post-fault period as demonstrated by the VDL2 curve colored by blue in Fig. 6. For instance, at time 4.78 s, the terminal voltage of 0.987 p.u. limits the I_{pcmd} to 0.987 p.u. Therefore, the terminal voltage of the solar power plant has an essential role to determine the maximum active power injection from the current limit logic shown in the equation (7).

The VDL2 table is one of the limiting factors in the current limit logic so that the active power cannot return to its pre-fault value. The following test case demonstrates the findings of modification of the VDL2 curve. The Ip3 in VDL2 is increased from 0.85 to 0.95 p.u., as shown in Fig. 6 with the assumption that more active power injection would be available after the change. According to the results shown in Fig. 7, the terminal voltage of the solar plant has been decreased as the result of the reduction of Iq. The low terminal voltage results in a lower Ip value in the VDL2 curve colored by orange in Fig. 6. Therefore, with the low terminal voltage, the active power output has been decreased during the post-fault period. As the conclusion, in this test, the increase of Ip3 in VDL2 curve could not resolve the active power drop issue during the post-fault period.

Another solution is to generate more reactive power to support the terminal voltage of the solar power plant. Therefore, the Imax in the test case is increased from 1 to 1.2 p.u. As the result, from the equation (5), the Iq capability is increased which results in the increase of the terminal voltage to 0.98 p.u during the post-fault period. The higher value of the terminal voltage results in a higher value of the Ip in the VDL2 curve. This causes the increase of active power output to 0.98 p.u during the post-fault period as depicted in Fig. 8. However, the active power does not recover to its pre-fault level because of the maximum amount of the Ip injection again limited by the VDL2 curve in equation (7).

For the purpose of this paper, to understand the current limit logic and recovering the active power to its pre-fault value after the contingency, the Ip values corresponding to terminal voltage at 0.8 p.u and 1.0 p.u are changed to 1.2 p.u (Ip3) and 1.2 p.u (Ip4), respectively as shown in Fig. 6, so the Ipmax is further increased in the equation (7) during these voltage range. This results in the active power recover to its pre-fault value as shown in Fig. 9.

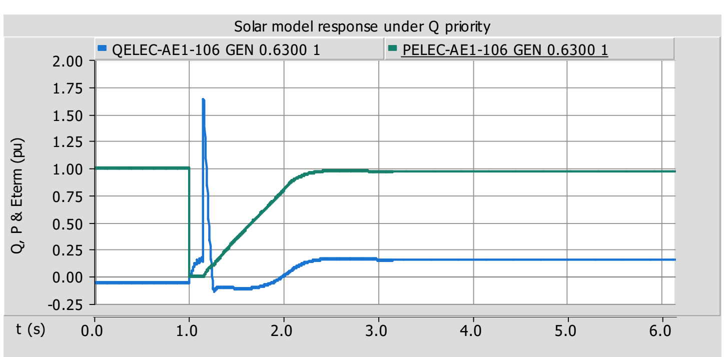

Fig. 3. Solar model response under Q priority

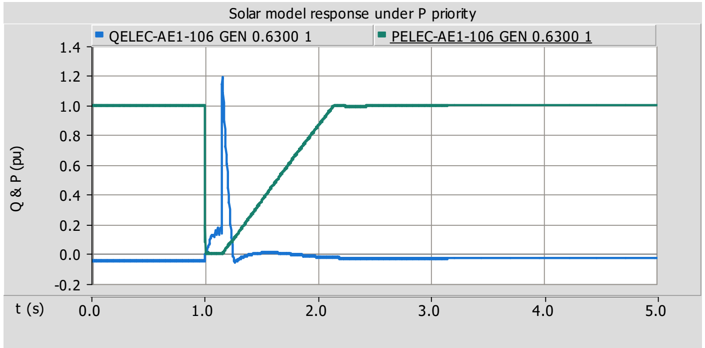

Fig. 4. Changed original case from Q priority into P priority

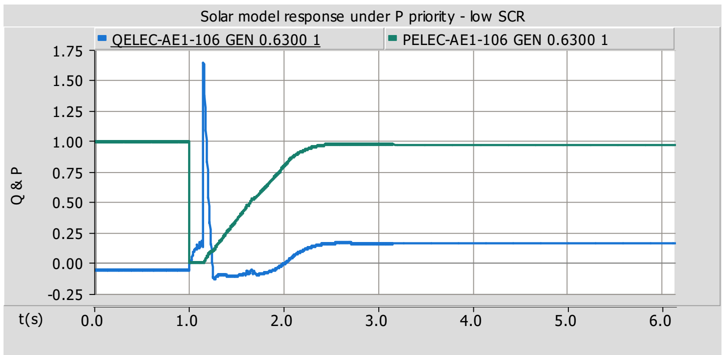

Fig. 5. PV plant dynamic response under P priority.

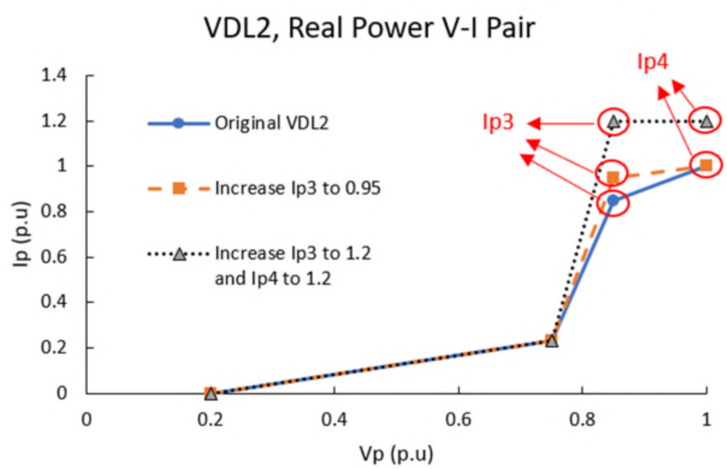

Fig. 6. VDL2, Real Power V-I pair

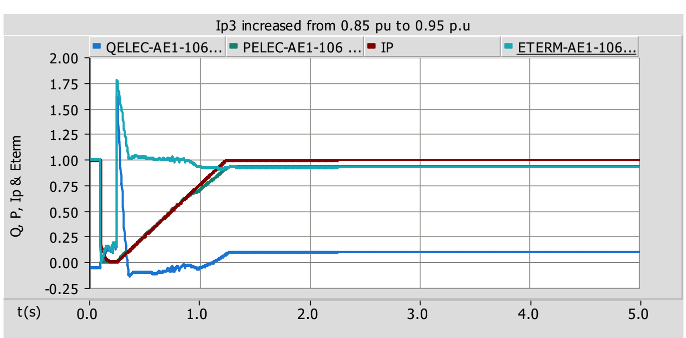

Fig. 7. Ip3 increased from 0.85 pu to 0.95 p.u

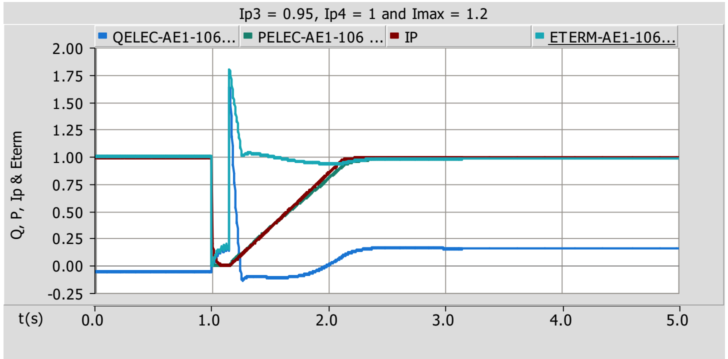

Fig. 8. Ip3 = 0.95 pu, Ip4 = 1 pu and Imax = 1.2 pu

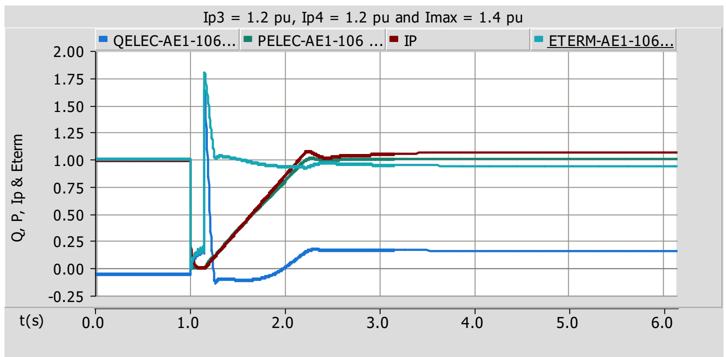

Fig. 9. Ip3 = 1.2 pu, Ip4 = 1.2 pu and Imax = 1.4 pu

4. CONCLUSION

With the increased demand for renewable energy sources (RES) around world, understanding of inverter model’s behavior becomes essential to system planning engineers. As demonstrated in this paper, the *P*- or *Q*-priority operating mode is a critical part of the inverter model response during a severe network disturbance, especially in networks with low SCR. The current logic limits play the main role in active and reactive power output. Different tests incorporated in this paper show the details of current logic limit tuning in the inverter control model to achieve a desired inverter output. The presented results provide useful information and suggestions for system planning professionals to understand the P/Q priority operating mode and current logic limit.

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