ACTIVE CONTROL OF DISTRIBUTION CONNECTED PHOTOVOLTAIC SYSTEMS FOR REDUCTION OF FAULT-INDUCED DELAYED VOLTAGE RECOVERY

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ABSTRACT

The phenomena of Fault Induced Delayed Voltage Recovery (FIDVR) is described, and illustrated with simulations. Impact of photovoltaic (PV) generation on FIDVR is shown, and efficacy of a new PV inverter control for mitigation is demonstrated.

INTRODUCTION

Electric power grids that serve certain types of customer loads are subject to a problem termed “Fault Induced Delayed Voltage Recovery” (FIDVR) [1]. End-user equipment, such as a modern air conditioner, is prone to stall during voltage depressions that accompany grid faults and other disturbances. The stall behaviour can create a high stress condition that prevents recovery of system (grid) voltage once the fault is removed. The delayed voltage recovery can result in undesirable relay actions, interrupted loads, tripped feeders and other disruptive impacts. Power systems in the south-western US have experienced FIDVR for more than a decade, and there is concern that the problem is getting worse. With the rapid growth of photovoltaic (PV) generation, many distribution systems subject to FIDVR are changing. This paper presents a novel method for mitigation.

ROOT CAUSES OF FIDVR

FIDVR events are cascading events that are initiated by an electrical fault on a portion of the transmission and distribution (T&D) system. Such electrical faults typically initiate fault clearing, however, the voltage may remain at a significantly reduced level for several seconds after the fault has been cleared. The extended voltage reduction is typically caused by high concentrations of induction and other motor loads with constant torque and low inertia that begin to slow down substantially and simultaneously with the voltage reduction. Some motors may slow down sufficiently to stall. As these motors slow down, they draw increased reactive power from the T&D system. Moreover, such stalled induction motors require high starting current to escape this locked-rotor condition. The combination of the simultaneous high reactive and real power demand results in system voltage remaining significantly depressed for a period of time, typically a few seconds, after the fault is cleared. This sustained depression can lead to tripping of distribution circuits due to excess currents, or to cascading voltage collapse through adjacent portions of the grid. The risk of FIDVR increases with the penetration of stall-prone motor loads, and it increases as the host power system short-circuit strength drops relative to the amount of motor load. The exact character of system behavior during these events is complex and difficult to predict, as nearly chaotic combinations of motor dynamics, relay actions and equipment protective behaviors, each of which may either reduce or increase system stress, tend to occur.

Inverter-based Compensation Systems

The concept of using inverter based systems to provide voltage support is well established, with much of development work dating back to the 1990s [2]. The power industry has offered purely reactive devices, under the generic name of “STATCOM”, for application at different voltage and device ratings. Devices with inverters coupled to energy storage devices such as batteries [3] or superconducting magnets [4] have been commercially available for some time as well. Devices in the rating range of a few MVA have targeted distribution system voltage problems associated with motor stall. [5].

Growth of Photovoltaic (PV) Generation

Photovoltaic (PV) generating systems are proliferating rapidly in much of the world, including systems that are known to be subject to FIDVR (e.g. the South-western United States). PV systems are often connected in distribution systems in close electrical proximity (e.g. the same household or business) to the loads (e.g. air conditioners) that misbehave.

The growth of PV generation tends to result in the displacement of synchronous generation. This phenomenon has been widely observed in Europe [6] and is being observed in the southwest US as well. This displacement tends to reduce the short circuit strength of the host grid, resulting in the concern that even systems which have not historically been at risk of FIDVR will become so with more PV.

However, the growth of PV also presents an opportunity to provide a powerful mitigation for FIDVR.

A NEW CONTROL FOR PV

PV systems, all of which rely on power inverters for their connectivity to the grid, have inherent capability to inject currents to the grid. Control of this current injection can be extremely fast, and can be used to help mitigate FIDVR. The basic premise of a new control [7] is to optimize the current injection of the PV four quadrant inverter that is connected in parallel or, in near electrical proximity to, the sensitive loads in order to maximize torque on stalled, or nearly stalled, induction motors. . The idea is to use the inverter to help return the stalled motors to normal operation. The control is subject to the limitations of the current delivering device and accompanying resource.

The control represents a substantial improvement over purely reactive compensation. Further it is novel, even with respect to devices that deliver active power, in that it dynamically adjusts the mix of active and reactive current injected through the trajectory of the system recovery in response to measured system feedback.

TEST SYSTEM

In order to illustrate the FIDVR phenomenon, and the efficacy of the new control, we introduce a relatively simple test system in Figure 1.

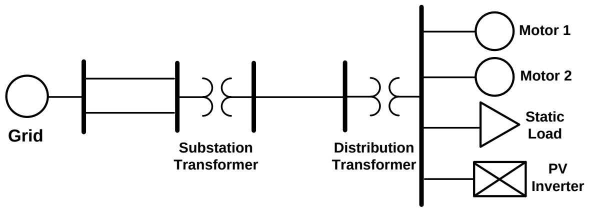

Figure 1 Test System

In this test system, the bulk power system grid is represented with a short-circuit equivalent (on the left of the figure) behind two parallel lines feeding a transmission/distribution substation. The substation transformer feeds a distribution line equivalent and a distribution transformer. The distribution load is represented as two *equivalent* induction motors and static load connected in parallel. The model also includes some passive shunt compensation and an inverter for a PV system (which we shall initially ignore). The approximately 21 MW of total load running at poorer than 90% power factor, is relatively heavy for the rating of the distribution system.

This simple topology is representative of distribution systems; and especially appropriate for radial distribution systems that are typical of North American systems. The results illustrated are generally applicable to stressed systems, including networked distribution systems that are more typically found in Europe and other parts of the world.

Generally there is relatively close proximity of smaller PV systems and load. Here they share a common node, but that is not a necessity for the control to be effective.

Illustration of FIDVR

FIDVR has been observed when faults occur on the host transmission system that serves the distribution system. In Figure 2, results of a simulated fault at the transmission bus of the substation are shown. The fault, which occurred at 0.5 seconds, is cleared a few cycles later by tripping one of the two lines feeding the substation, thereby reducing the system short-circuit strength. The fault deeply depresses the voltage at the load bus serving the motors. Once the fault is cleared, the voltage recovers to about 60% of nominal. But it “hangs” at this depressed voltage for about ½ a second before recovering to near nominal. In a more healthy system, the voltage would recover within a few cycles of fault clearing. One of the motor speeds (ω) can be seen to drop during the fault as well. The relatively slow recovery of speed matches, and is symptomatic of FIDVR. In Figure 3, the motor active (P) and reactive (Q) powers are shown. Notice that the reactive power consumption during the recovery time is about 14 MVAR – several times the normal VAR consumption and nearly double the 7 MW nominal rating of the equivalent motor. It is the stress of this greatly elevated reactive consumption as the motor attempts to create enough torque to re-establish normal speed that causes FIDVR: The transmission system simply cannot deliver enough active and reactive current to re-accelerate the motors. Had the fault been longer, the post-fault system weaker, or the motors even more heavily loaded, recovery would have failed altogether and the motor would stall (as will be shown below).

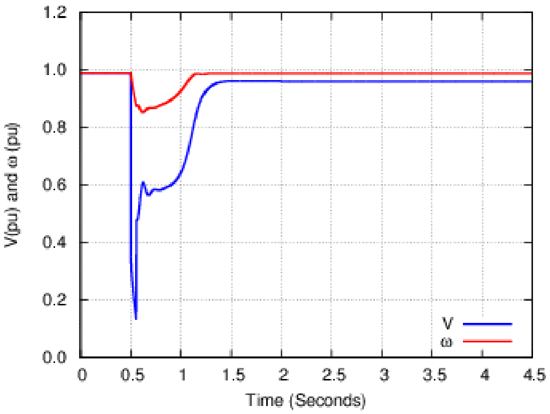

Figure 2 Fault Induced Delayed Voltage Recovery

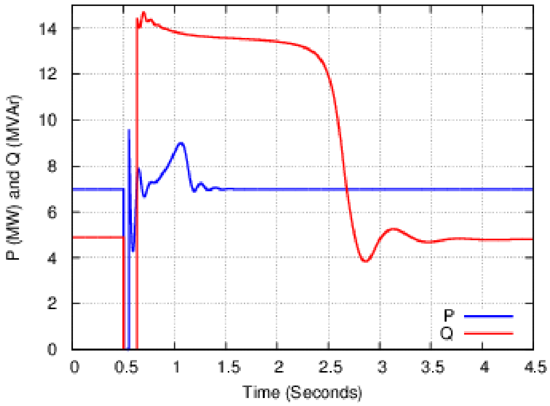

Figure 3 Motor Active and Reactive Power for FIDVR

FIDVR with PV and Mitigation

The simulations shown in this section have the PV system running and providing 6 MW of generation. This de-stresses the system somewhat in the pre-fault state. Ordinarily, PV systems do not provide much, if any, voltage support. Here we *optimistically* assume that the PV inverter is capable of delivering reactive current up to an over-excited power factor of 0.90. We further assume that the PV is capable of, and *allowed to*, ride-through of the fault and to provide voltage support. In jurisdictions where IEEE standard 1547 [8] is in effect, neither of these assumptions may hold.

In the sequence of Figure 4 to Figure 7, simulation results for three control strategies are shown. For each case, the transmission system is subjected to an 8 cycle fault, cleared by opening one of the two transmission lines. The figures show traces of the load bus voltage, one equivalent motor speed, and the active (P) and reactive (Q) power of the PV system.

First, we examine the "default control" case, with the PV system subject to the optimistic assumptions just enumerated. These are the blue traces. For this case, the voltage and motor speed do not recover: the equivalent motor is on a trajectory to complete stall and interruption. Depending on other protection and control not modelled here, this failure could lead to more widespread problems. Other, less robust PV control (e.g. unity power factor control) would result in similar or worse behaviour.

Second, we examine the "reactive only" control case. These are the red traces. In this case, the PV inverter responds to the disturbance by using its entire current rating to deliver *reactive* current during the fault and the post-fault recovery period. Notice that the voltage and motor speed eventually recover, with the bus voltage rising above 90% at about 2 seconds after the fault inception. This represents a huge improvement in system performance. This so-call Q-priority control represents the sort of improvement that might be realized by the addition of stand-alone dynamic reactive compensation devices, such as STATCOM or static var compensators (SVC).

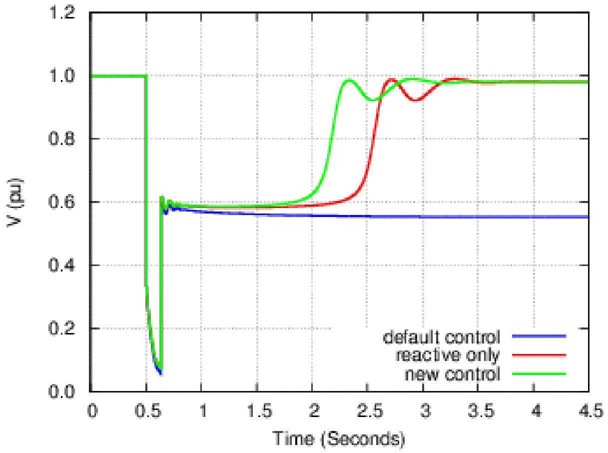

Figure 4 Terminal Voltage – Different PV Controls

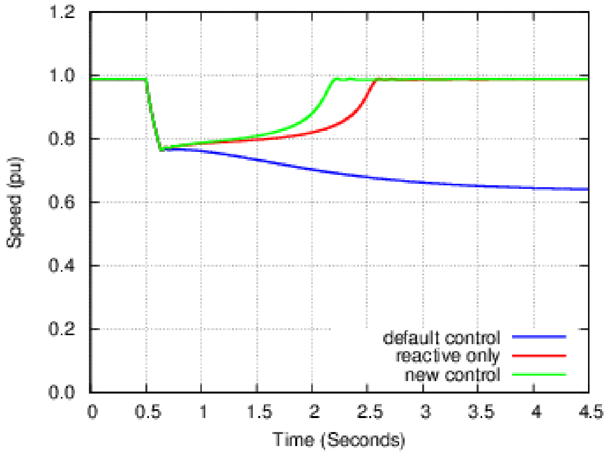

Figure 5 Motor Speed - Different PV Controls

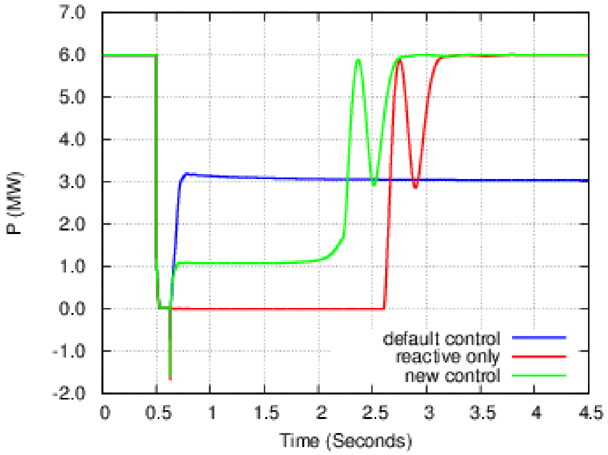

Figure 6 PV Active Power Output - Different Controls

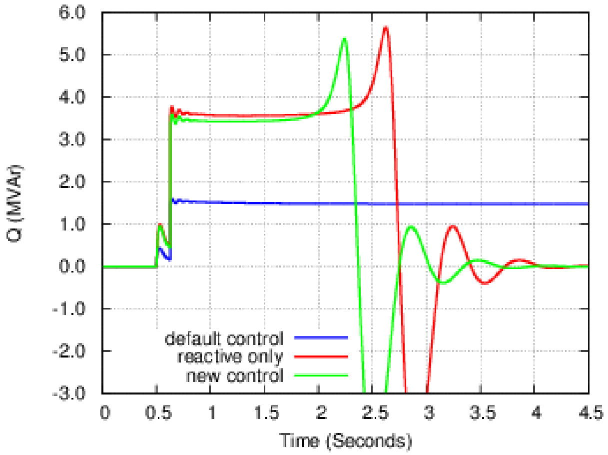

Figure 7 PV Reactive Power Output - Different Controls

In the power system engineering community that is particularly concerned with FIDVR, this class of solution – the addition of utility sponsored, dynamic reactive compensation – has been pursued, with both utility scale SVCs and distribution scale STATCOMs being added to grids in the US [1].

Finally, we examine the performance with one, relatively simple version of the new controls. The performance is shown in the green traces. In this case, the control was tuned to delivers a fixed, current power factor when the inverter is in limits during significantly depressed voltage conditions. In this case, the power factor of 0.3 over-excited (i.e. delivering reactive current to the grid) was found to produce the shortest recovery time. Notice that the recovery, as measured by the time until the voltage rises above 90%, is improved by about ½ second – roughly 25%. Inspection of Figure 6 and Figure 7, shows that both the active and reactive power deliveries are between the bounds described by the default control and the reactive only control. Dynamic control of the current injection power factor based on feedback from measured system conditions is part of the control, and will be demonstrated in subsequent papers.

CONCLUSION

Examples in the paper show that the new control for Photovoltaic (PV) inverters is effective at mitigating FIDVR. The control produces substantial systemic improvements over the default controls on PV, even with rather optimistic assumptions about those controls. Further, the control also produces better FIDVR recovery than use of controls that concentrate solely on reactive compensation. With the increased penetration of PV, reduced system strengths due to displaced synchronous generation, and heavier air conditioning loads, such controls may prove to be highly valuable in maintaining and improving system security in systems with substantial amounts of PV generation.

That the control does not necessarily involve any added equipment rating beyond that normally required for the PV inverter means that the control could be an economic means to mitigate a substantial and growing risk to the reliable operation of distribution systems. It is a substantial benefit that distribution connected PV systems, in the US at least, are likely to be deployed in close electrical proximity to the air conditioner loads that are the primary cause of FIDVR.

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