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1.0 Introduction

Fault Induced Delayed Voltage Recovery (FIDVR) is a phenomenon observed in the electric power grid in which, as the phrase suggests, is a sustained voltage depression after a fault, eventually rising after some time. A descriptive plot is shown below in Figures 1. In this plot the depressed voltage is observed just after the fault is cleared. The voltage recovery time varies depending on the event, but typical durations range in seconds to tens of seconds. The voltage slowly recovers as the A/C load trips off by its internal protection; once then entire stalled A/C trip off the system, the voltage is higher than the pre-fault level. Reacting to the high voltage, the capacitors switch off to reduce this overvoltage. This is observed in Figure 1 as the voltage tends back down to a nominal level. Finally at the far right of the plot, we note that the voltage subsequently lowers to a level that is again below the pre-fault level. Eventually, on a timescale beyond that shown in Figure 1, system controls will again normalize the voltage.

The initial depressed voltage is troubling because it represents a relatively long period in which the voltage is not controlled. It persists for seconds, instead of cycles. There is justifiable concern that this behavior could directly lead to a widespread outage or leave the system vulnerable to a significant outage as the results of another disturbance. For the same reason, the lower voltage at the end of the trajectory is potentially vulnerable to a second disturbance, especially if key network voltage support is temporarily lacking. Many small outages and several larger outages are attributed to the FIDVR phenomenon.

![Figure 1. Voltage during a FIDVR event (courtesy of D. Kosterev, BPA).](image-url)
Fault-induced delayed voltage recovery is not a new phenomenon. While most reports of events are anecdotal, there are a few published papers describing certain events and studying the causes. In regions with a high percentage of air conditioner loads, the problem persists.

In their 1992 paper\(^1\), engineers from Southern California Edison discuss voltage recovery problems they had encountered in the desert regions that they serve. The largest event involved a 1000 square mile region. They also mention other similar incidents at other utilities, including a major blackout in Memphis in 1987.

In his 1997 paper\(^2\), Florida Power and Light Engineering John Shaffer reports eight incidents of delayed voltage recovery over the preceding decade. These resulted in 200-825 MW of lost load. He mentions a 1988 event with a 10-second voltage recovery. He also points out that most of the load loss was actuated by device protection (in contrast to system controlled protection).

More recent events are not described in journal articles, but have been presented at conferences and workshops. Southern California Edison continues to observe FIDVR events and they are leading research to study causes and propose solutions. One paper presents an undervoltage protection scheme and also shows a plot of a recent disturbance with a 30 second voltage recovery time.\(^3\)

The state of the art in FIDVR reporting and research has been presented at two recent DOE workshops, in 2008 and 2009. The presentations from these workshops and the related NERC whitepaper summarize present activity in this area.\(^4\) Events mentioned in presentations at the 2008 workshop include

- More than 50 events observed in Southern California Edison (Devers, Antelope, Vally, Lugo, Rector, Villa Park). The Lugo plane crash resulted in 3500 MW lost load.\(^5\)
- Several incidences in the Arizona Public Service;\(^6\)
  - 2 Pinnacle Peak Capacitor Faults. The second resulted in 1000 MW load loss.

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4 2008 workshop presentations are available at [http://sites.energetics.com/acstallingworkshop/agenda.html](http://sites.energetics.com/acstallingworkshop/agenda.html)

The 2009 workshop presentations are not yet posted. The NERC white paper is available at [www.nerc.com/docs/pc/tis/FIDV_R_Tech_Ref_V1-1_PC_Approved.pdf](http://www.nerc.com/docs/pc/tis/FIDV_R_Tech_Ref_V1-1_PC_Approved.pdf).


o Hassayampa 500 kV Fault. Loss of 440 MW load and 2600 MW generation.

- Southern Company\(^7\) reported on the Union City event in which 1900 MW of load was lost. Almost all the load was tripped by induction motor protection.

At the 2009 FIDVR workshop emphasized the following items:

- Studies suggest that SVCs help alleviate the problem but does not prevent A/C from stalling therefore the FIDVR events may still occur
- Studies also suggest that undervoltage protection devices in A/C units prevents the FIDVR events but creates another problem that is instantaneous overvoltages at high penetrations for these devices.
- The proper solutions is to have the A/C units ride thru the voltage transient or trip only the A/C units that stalled
- NERC TIS will be creating a site under their website to incorporate FIDVR so that other utilities in the country learn from the California experience.

It is clear that FIDVR events can be consequential, they persist, and they pose a challenge to the reliable operation of the power grid.

In this report we summarize some of the research on this topic and discuss potential solutions. In the next section of this report we present the underlying causes that drive FIDVR events, predominately the stalling of compressor-driven induction motors. In the following section we discuss potential solutions. These include the changes that could be made to units, and system controls that could mitigate FIDVR. We also discuss the challenges with implementing the solutions.

\(^7\) Taylor, “Recent Experience with Fault Induced Delayed Voltage Recovery,” DOE Workshop, April 22, 2008.
2.0 FIDVR Phenomenon

To consider solutions to avoid or mitigate FIDVR, it is necessary to study the cause. The physical mechanism to explain the phenomenon is related to the end-use load characteristics of air conditioners and other motor-driven compressor loads. To understand how these end-use devices react to faults, and how they can effect a slow-to-recover depressed voltage, it is necessary to consider their operation in detail.

For a compressor, the average mechanical load faced by an induction motor increases as it literally drives pistons (reciprocating compressor) or turns a “scroll” (scroll type compressor) to compress a gas. The more it is compressed, the greater the operational motor torque is needed. The electrical torque capability for an induction motor is nonlinear and depends on its operating speed. In Figure 2 we show a typical “torque-speed” curve for an induction motor.

![Torque Speed Curve for Motor](image-url)

**Figure 2. Torque Speed Curve for Motor.**
The horizontal axis in Figure 2 is the motor speed expressed in electrical radians/second, and ranges from zero (blocked rotor or stalled) to synchronous speed: $2\pi 60$ (60 Hz). The vertical axis is torque. Superimposed on this plot are two straight-line mechanical load torque curves; one is a low load line meant to represent the compressor when it has been inactive for several minutes. The high load line represents the normal operating load under compression. Important for our discussion is note that the zero-speed electrical torque is less than mechanical torque load. (We discuss this more below.)

When a compressor initially turns on after a few minutes of inactivity the load torque is low, and the motor quickly accelerates to normal high-speed operation. This is denoted by point “A” in Figure 2. With increased compression the mechanical load torque increases and operation tends to point “B” on the plot. This is the normal operating condition for the compressor, and this torque represents the equality of average load torque and electrical torque. For this level of mechanical load we note a second equilibrium denoted as “b” in the plot. Dynamically this other point is unstable.

For purposes of using Figure 2 to describe the phenomenon of FIDVR, we note that this high load torque line intersects the zero-speed axis at a point higher than the electrical load torque. That is, the load torque exceeds the zero-speed torque capability of the motor; if the motor were to stall, it would not be able to restart. And that is exactly what happens: a temporary fault drops the voltage low enough for air conditioner motors to stop, and they are unable to restart when the fault is cleared. The stalled motors draw significant current which causes the observed depressed voltages. Protection equipment eventually remedies this situation.

Motors have two types of protection that are relevant: Contactors that disconnect when the voltage drops below 40%, and an inverse-time characteristic current relay (thermal protection). In practice the stalled voltage is typically larger than the 40% threshold, so the stalled motors stay connected to the grid. The thermal protection does actuate, removing the stalled motors from the grid. As the motors trip off-line, the voltage recovers. The motors don’t trip off simultaneously (3-15 seconds according to one manufacturer8), so the recovery appears gradual. The “delay” in “delayed voltage recovery” is due to the delay in motor thermal protection operation.

Once the motors are offline, they will remain offline for some time, until the compressor pressure equilibrates and the motor can restart. (Readers with newer air conditioners, dehumidifiers and other compressor-driven loads may be familiar with this characteristic: these appliances will delay a few minutes to restart after they have been turned off.) The grid response to the accumulated loss of load is to increase the voltage above pre-fault level. As previously noted, network controls will react to then lower the voltage.

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The second vulnerable region occurs when air conditioners turn back on. This increased load draws the down the voltage, and without reactive power support the system is potentially susceptible to subsequent events.

The phenomenon as described in the preceding paragraphs is generally accepted as the fundamental mechanism, and it is the mechanism described in the early papers. More recent testing and model development conducted in the WECC supports this description of the FIDVR mechanism.

There are a few recent additions to the knowledge in this area that are worth mentioning. The models that are examined in the early papers represented an induction motor driving an assumed constant load torque. There are two deficiencies related to the mechanical load in that model: the inertia of the compressor is over-estimated, and the mechanical load torque is not constant. Both of these points help explain the very fast stalling time observed in laboratory tests and in the field. The air conditioner load appears to stall during the fault - measured in cycles. In the models used in the early papers the stalling of the motors is simulated by assertion – when there is voltage drop below a certain threshold, the motor is declared to be in a stalled state. Whereas simulation of the motors using parameters given in the papers do not necessarily capture such a quick stall. In Shaffer’s paper, critical clearing times are given for three motor models subject to faults of varying severity. For those severe faults with a fault voltage of 0 volts, the critical clearing time to avoid a stall ranges from 2 to 6 cycles. For fault voltages in the range of 50-55% nominal, the critical clearing time ranged from 5 to 21 cycles, depending on the initial load torque (with the range of 19-21 cycles for 1.0 pu torque). The tests in Williamson paper demonstrated that the air conditioners stalled within 5 cycles (their fastest test) for fault voltages below 60%. Recent laboratory tests note this quick stall - within 3 cycles (their fastest test).

The models and measurements can be reconciled. First the assumed inertia in the early simulations is too large ($H = 0.28$ seconds). After recent testing, a compressor was disassembled, the rotor pulled, and its inertia was estimated to be $H = 0.03$ seconds. Laboratory tests suggest an inertia of $H=0.03$ to $0.05$ seconds. This suggests a much greater propensity to stall.

Second, the load torque is not constant. One of the comments on the Shaffer paper suggested that the compressor torque may not be constant. At the time, design engineers had informed

9 Williams et al; and Shaffer.
10 Shaffer.
11 Williamson et al.
13 Pal, M.K, Discussion of “Air Conditioner Response to Transmission Faults.”
him that the torque could be considered constant for a few seconds after a fault. Recent conversations with air conditioner manufacturers indicate that the load torque is position dependent as the motor drives pistons (reciprocating) or turns the off-center scroll. The compressor load torque resembles a strong triangle wave, and the peak mechanical load torque may exceed peak electrical torque during operation. The compressor relies on the motor inertia to carry through this peak.

The WECC Load Model Task Force has been active in developing improved load models to simulate FIDVR phenomenon. This work has been carried out in large part with support from the California Energy Commission. This work has resulted in the development of two models for simulating compressor-driven motors. The static performance model captures the running and stalled voltage-dependent load characteristics of the motors, with a voltage-specified transition point. A dynamic phasor model suitable for use in positive sequence simulations was developed from a traditional single phase motor model. Both are being incorporated in the standard simulation packages used to study power system behavior in the WECC.

With this understanding of the FIDVR we turn to potential solutions.

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14 WECC Load Modeling Transmission Research Project, CEC Contract 500-02-004.


3.0 Solutions

Eliminating FIDVR events will be challenging. The NERC whitepaper emphasizes this point in its executive summary: “FIDVR events can – and have – occurred following faults cleared in as little as 3 cycles! The number and impact of FIDVR events can be decreased, but their elimination in the near term is unlikely.” (their emphasis.) To eliminate these events, it would be needed to prevent the air conditioner motors from stalling. Even if new air conditioners were manufactured to avoid stalling, wide-spread use of new units to replace the existing installed base would take many years to change.

In this section we discuss these issues and summarize strategies for mitigating FIDVR problems. We consider customer-level solutions and system level solutions.

3.1. Customer-Level Solutions

The most effective controls may be implemented at the source of the problem: the air conditioning units. There are at least two changes that could reduce FIDVR event or severity of events:

1. Low voltage ride through. Units could be designed to withstand low voltage conditions for a short time to prevent stalling during the fault.
2. Low voltage disconnect. Units could be quickly tripped when the voltage drops to a point at which they would stall. Then, the units would return to operation after random delays, to stagger the return of load.

The first item is ideal in that it would eliminate the problem for normally cleared faults. The application of this solution would require not insignificant changes to the present design of units. One could consider over-sizing motors such that the no-load electrical torque exceeds the normal mechanical torque, with the idea that the motors would be able to restart upon re-excitation after the fault clearing. However, it is not clear that this would be successful – if motors did stall during the fault but attempted to restart simultaneously after the fault, it is likely the voltage would remain low initially. This approach would likely lessen the duration of the event, as some motors trip off-line others may succeed in restarting. Alternatively, one could increase the inertia of the motor/compressor to provide stored mechanical energy with which to ride through the event. Finally, local electrical energy storage coupled through power electronics (also driving the motor), could be implemented to achieve a low voltage ride-through capability. These latter two solutions are technologically feasible, but would increase the cost of such units. It should be expected that manufacturers would be reluctant to implement these without further and equal motivation. Any such changes would likely required modification of standards so that all manufacturers are provided the same objective.

The second item – low voltage disconnect – is practical, and offers the opportunity for effective retrofitting. This type of protection could be implemented on new units, and while it would increase costs, it is not likely be large compared to the solutions mentioned above. Also, this solution could be implemented by under-voltage relays or digital thermostatic control. The low voltage disconnect and delayed reconnect could be programmed into a modern thermostat.\(^{17}\) A program to retrofit digital thermostats could reduce the FIDVR

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\(^{17}\) To use thermostatic control, the thermostat would need some detection of low line voltage. Otherwise, an under-voltage relay can perform a similar function.
problem when coordinated with system controls, and it should be considered. (See Lu et al for an analysis of under-voltage protection schemes in this context.19) More generally, new communication and control technologies that enable a customer to actively participate in grid function (i.e., the “smart grid”) could be applied to FIDVR problems.

Unfortunately, the low voltage disconnect solution does not address all of the problem. It should effectively eliminate the delayed voltage recovery portion of the behavior at the expense of immediate loss of load. This will likely result in immediate overvoltages in the system. System level controls would need to be designed to handle this situation.

3.2. System Solutions

System solutions are covered in detail in the NERC whitepaper. Here we draw on the discussion in that document. These solutions include

1. Reduced fault clearing time. This may reduce the occurrence of events. Given the experience with the very short time to stall for compressor-driven motors, this solution will not eliminate all events.
2. Controlled reactive power support. Generators and SVCs can provide controlled reactive power support to lessen the duration and severity of a delayed voltage recovery event.
3. Limit Impacted Load. Specifically design the system to section the load to limit its size in areas particularly vulnerable to FIDVR events. This should help contain the events.
4. Special Protection Schemes (Remedial Action Schemes). A transmission level protection scheme could be designed to contain the effect of a FIDVR event.
5. Under voltage load shedding

In practice, generators and SVCs have been installed to mitigate these events. APS has installed generation in Pheonix, and plan to install SVCs. Southern Company has installed SVCs.

Further studies are needed to analyze the impact of these solutions. Experience and simulations suggest that reduced clearing times will not eliminate all events – the motors stall during faults. At the grid level, controlled reactive power support seem to be the most promising solution. Appropriate devices are expensive, however, and they may not be able to prevent the events, though significant reduction in impact should be expected. (See the Pourbeik presentation that includes a simulation with and without SVC or synchronous condensor support.19)

Items 3-5 in the list above are intended to limit the scope of an event once it occurs. Item 3 is local, item 4 is at a higher level, and item 5 is offered as a measure to stop a fast-acting voltage disturbance from transitioning into a slow-acting voltage collapse. The NERC report notes that item 4 may actually be non-compliant with existing rules, and that this needs attention.

The last item, may or may not improve the situation depending the nature of energy savings devices that are used.

In all cases, further study is needed to assess the success of any strategy. Most of the intuition used to consider such options follows balancing power and reactive power under FIDVR scenarios. For those solutions that quickly remove the stalled motors from service, or the feeders that serve them, one needs to be concerned about initiating dynamic instabilities. Detailed studies are needed to ensure there are no unintended consequences.
4.0 Summary and Recommendations

Fault Induced Delayed Voltage Recovery is a serious problem threatening the reliability of the electric power grid. Numerous events have already occurred, some with significant load loss. It is a challenging problem whose fundamental characteristics are driven by load behavior that is largely beyond the control of transmission operators. As Baj Agrawal points out in his presentation,20 “Normally the 12 kV voltage is a slave to the transmission system voltage. However, due to stalled motors, the 12 kV voltage sags heavily and pulls the transmission system voltage lower.”

The most effective solutions are those that can react at the site of the problem. These can also be the hardest to implement. Changes to air conditioner units to provide low voltage ride through would add additional manufacturing expense. Without standards with common requirements for all, manufacturers have a disincentive to implement such changes. Implementing new standards will take time, and even more time will pass before new units dominate the installed base. Digital thermostatic controls are promising; research and perhaps a pilot program should be put in place to determine their effectiveness. One could generalize the use of thermostatic controls to a more distributed use of technology to enable traditional customers to offer valuable grid support. Such efforts fall under the now popular title “smart grid.” As such technologies advance, an eye towards FIDVR mitigation is warranted in those areas susceptible to events.

System level solutions focus on containing and mitigating events. Controlled reactive power sources are essential for this purpose. Studies to assess and quantify their effectiveness are needed. Long term monitoring of events in areas with new generators and SVCs will help determine the value of these resources, and guide additional protection as needed. Research programs for such monitoring and analysis should continue.

It is imperative that California investigate further the way to mitigate the A/C stalling to prevent the FIDVR events that can have a negative impact in the grid, or in a drastic scenario compromise the grid operation like the 2003 northeast blackout event.

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