by Russel W. Paterson, TVA

Large motor impact

The two main goals of a transmission line protection scheme are to successfully clear faults and to successfully reclose the circuit once the fault has been cleared. The chances of success are greatly reduced in the presence of significant tapped motor load if the presence of this motor load isn't properly considered and proper scheme adjustments made.

Biographical Sketch

Russell W. Patterson is Manager of System Protection & Analysis for the Tennessee Valley Authority (TVA) in Chattanooga, Tennessee.

As Manager of System Protection & Analysis he is responsible for the setting of all protective relays in the TVA transmission system and at Hydro, Fossil and Nuclear generating plants. His has responsibility for ensuring that TVA's protective relays maximize the reliability and security of the transmission system. This includes setting and ensuring the proper application and development of protection philosophy for the TVA.

Prior to his position as Manager of System Protection & Analysis he was Manager of Advanced Network Applications (ANA). The ANA group is responsible for the real-time network analysis applications such as the Areva State Estimator, Telegyr State-Estimator, and PowerWorld in support of TVA's Reliability Operations function.

Prior to his position as Manager Russell was a Project Specialist in System Protection & Analysis and was TVA's Power Quality Manager responsible for field and customer support on PQ related issues and disturbances.

Russell is a member of the IEEE Power System Relaying Committee (PSRC) and an active member of the Line Protection Subcommittee. Mr. Patterson earned the B.S.E.E. from the Mississippi State University in 1991.

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On August 6, 2005 TVA experienced the trip of a distribution substation by a misapplied underfrequency load shedding relay (UFLS) that operated on the decaying frequency of the regenerative voltage from motors at a large pulp and paper mill located adjacent to the distribution substation. Figure 1 below shows the arrangement with the mill and distribution substation tapped on the same line. The single machine shown is representative of the entire plant motor load as a whole.

Figure 2 is an oscillograph captured by the microprocessor UFLS relay at the distribution substation showing the A-phase voltage along with measured frequency at the distribution substation low-voltage bus (13kV) during the event. The underfrequency element in the relay is already asserted prior to the beginning of the oscillograph as the frequency had already decayed to just under 52Hz by that time. The frequency estimated by the relay increases at points, due to the unsuccessful high-speed reclose by the utility breakers (just after the 0.1 second mark) and the subsequent interaction between the various motors at the neighboring pulp and paper mill.

This event was analyzed and fully described in the paper "Analysis of Underfrequency Load **Shedding and Reclosing** into a Motor Load on a TVA 161 kV Transmission Line" presented to the 9th Annual Fault and Disturbance Analysis Conference May 1-2, 2006 in Atlanta, GA. The analysis of this operation brought to light, as most any thorough event analysis does, the discovery of other hidden problems.

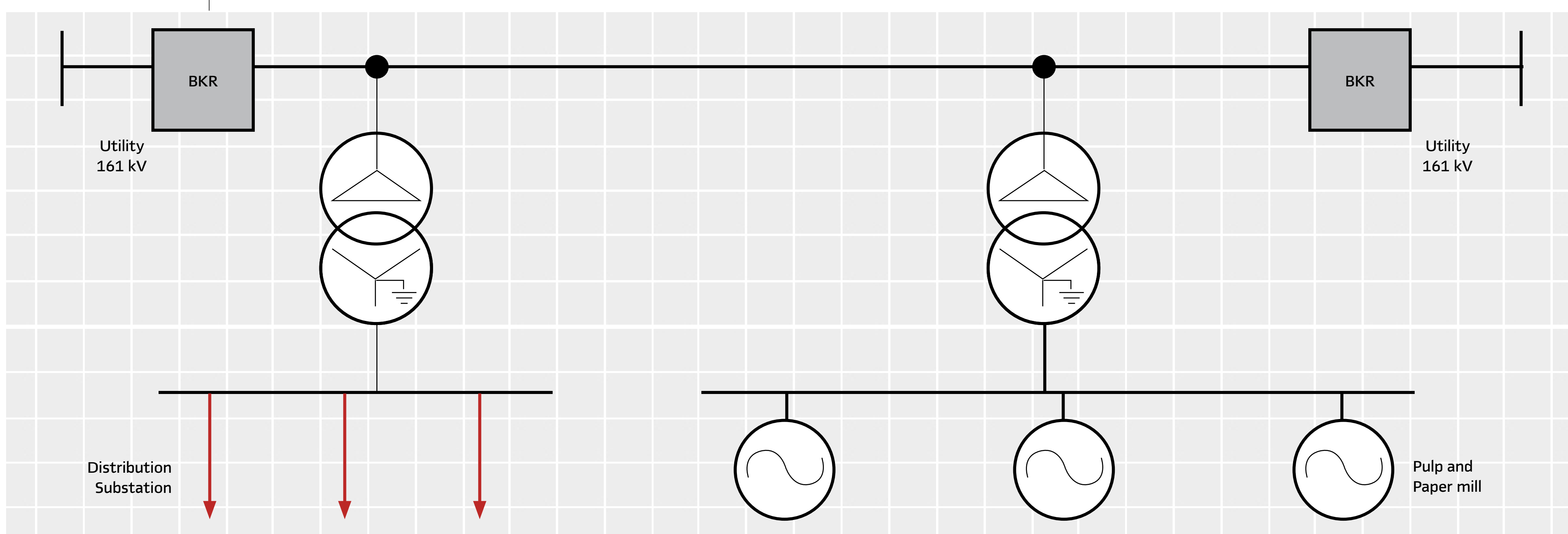
The two main goals of a transmission line protection scheme are to successfully clear faults and to successfully reclose the circuit once the fault has been cleared. The chances of success are greatly reduced in the presence of significant tapped motor load if the presence of this motor load isn't properly considered and proper scheme adjustments made.

When faults occur on the transmission line the utility protective relays at each end detect the fault and initiate tripping of their respective breaker (BKR in Figure 1). If the transmission line is protected by pilot relaying (affording high-speed breaker tripping at both ends for faults along the entire length of the line) then it likely has high-speed reclosing implemented as well. High-speed reclosing is delayed a minimum time after the breakers have opened to allow the fault ionization path to dissipate before attempting to reclose the breakers and restore the circuit. A typical high-speed reclose at 161 kV occurs 20 cycles after the breakers have tripped and is a "blind" reclose meaning it occurs regardless of line condition (as opposed to a synchronism check reclose or a dead-line reclose).

In the case pictured in Figure 2, the voltage on the transmission line doesn't go to zero immediately after the utility breakers are opened due to the tapped motor load.

This effect is due to the motor's regenerative (sometimes called "residual") voltage that exists due to the fact that the machine rotors are still spinning and a decaying rotor flux is present. In induction machines this flux is a trapped flux present at the moment the utility breakers disconnect the motors. In small motors it will generally decay in a few cycles but in larger machines it may require several seconds to decay to zero. In the case of synchronous machines this flux is due to the presence of field current and will likely result in much longer sustained regenerative voltage. The

1 Typical tapped customers on bulk transmission line



effects of the rotor drive train and connected load are important as well. Some loads tend to quickly retard the rotors rotation while others tend to sustain rotation. There are many factors that influence what this regenerative voltage will be and its rate of decay such as connected load inertia, mix of induction and synchronous machines, mix of small and large machines, mix of low and high-speed motors, etc.

Most authors on the subject are in agreement that reclosing should not occur on motors unless their voltage has decayed below 25-33% which may require several seconds for industrial motor load typically found in plants directly served from transmission level voltages (steel mills, pulp and paper plants etc.). The presence of the regenerative voltage acts to maintain the ionization path such that the subsequent high-speed reclosing results in a re-establishment of the fault. This requires the utility protection to initiate tripping of the breakers again to clear the fault, making the high-speed reclose unsuccessful. This fruitless attempt to re-energize the transmission line results in additional fault duty on the utility equipment with no benefit.

Beyond the negative impact on the utility protection system is the negative impact on the connected motor load. Immediately after the motors are disconnected from the utility grid they begin to slow down. As they do they begin to go out-of-step with the rotating mass of the collective utility generation. By the time the high-speed reclose occurs the regenerative voltage on the motors and the utility equivalent voltage are out-of-phase. If the regenerative voltage is still above approximately 25% then this out-of-phase reclosing can result in immediate or cumulative damage to the motors due to excessive current stresses on the windings. A typical design maximum momentary voltage of a motor is 125%. If the regenerative voltage on the motor is 25% of normal and it is 180º out-of-phase with the utility when the high-speed reclose occurs it will experience an instantaneous voltage of 125% of normal.

The following is a plot of RMS voltages captured by a power quality monitor on the low-voltage motor bus of the pulp and paper mill for the August 6, 2005 event (note that time zero in this plot isn't the same point in time as the time zero in Figure 1). This plant has a mix of large induction and large, slow-speed synchronous generators. **The plot shows the** motor regenerative voltage immediately after the utility system breakers trip and the subsequent unsuccessful high-speed reclose attempt. Approximately 5 seconds later a second reclose attempt occurs and is successful.

The high-speed reclose is evident near the 0.4 second mark (approximately 23 cycles after initial trip). The monitored bus is the 4,160V motor bus (2,400V phase-neutral). At the start of the plot (t = 0) the voltage is near 1.0 per-unit. Immediately after the transmission line breakers trip you can see that the bus voltage is maintained by the decaying regenerative motor voltage. Approximately 23 cycles into the event (t = 0.38 seconds) the transmission line breakers reclose to energize the line. They immediately trip back out as the fault ionization path has been maintained by the regenerative motor voltage and the fault arc is re-established. This reclose also hammers the connected motors with an out-of-phase reclose. The next reclose in the transmission system protection scheme is referred to as a dead-line reclose and occurs just after 6 seconds (t = 6.1) and requires that the line be dead prior to breakers closing. This reclose is successful and service is restored to the tapped loads.

Figure 4 shows another plot of data captured on a different day by this same PQ monitor when the plant was disconnected from the utility grid (no automatic reclosing occurred). This is a good graphic showing the regenerative motor voltage and its decay as motors spin down and contactors dropout etc.

Had a high-speed reclose occurred (around the t = 0.38 seconds mark) the regenerative voltage on the motors would have been just under 60% of nominal.

$$V_M = 0.06 \angle 120^\circ - 1.0 \angle 0^\circ$$

$$V_M = 0.04 \angle 158^\circ$$

Depending on the phase angle of this regenerative voltage relative to the utility system voltage this likely would have resulted in a serious out-of-phase reclose event.

For example, if the regenerative voltage at this point in time had a magnitude of 60% at a relative phase angle of 120º and the power system being at 100% voltage and zero phase angle the resulting voltage suddenly applied across the motors would have been as calculated below.

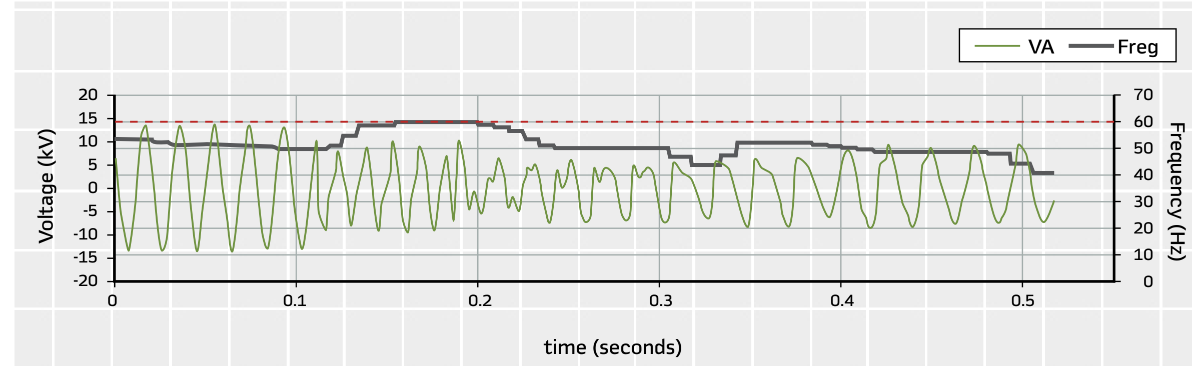
This reclose would have resulted in 140% voltage being suddenly applied to the motors (recall that motors have typical maximum design voltage of 125%).

In many cases the industrial plant engineers are not aware of the issues related to fault clearing and reclosing at the utility voltage level. They may not even be aware of the reclosing setup used on the feed to their plant or of the potential for immediate or cumulative damage to their motors that can occur during reclosing.

Reclosing requires careful consideration on transmission lines feeding industrial plants

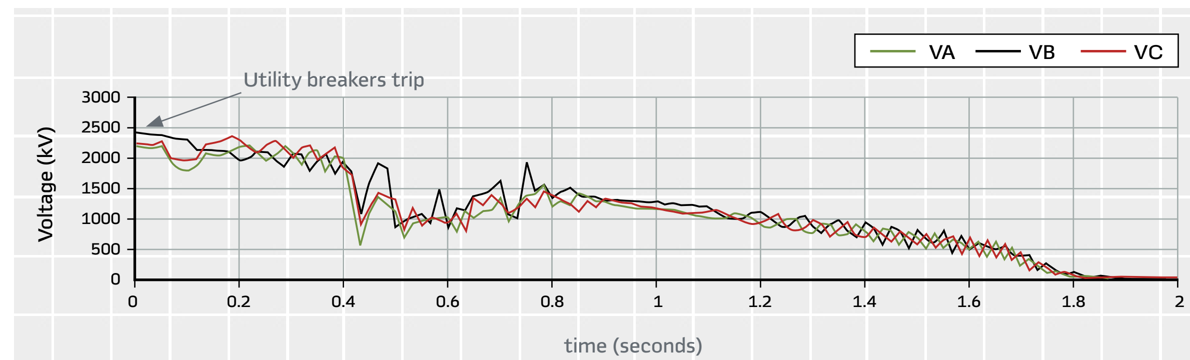
2 UFLS Relay Oscillography

A-phase voltage and frequency measured at distribution 13kV bus



3 Motor Bus RMS Voltages

First 2 seconds of RMS voltages captured by PQ monitor during event



4 Motor Bus RMS Voltages

First 2 seconds of RMS voltages captured during plant disconnect from the utility grid