An Intelligent Controller for High-Voltage Power System Applications

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Abstract: This paper describes advanced instrumentation used to control the switching of shunt compensation devices on a major 525 kV electric power transmission line. Occasionally electrical power systems are over-stressed, and become unstable. Electric utilities have installed special global control schemes designed to correct unstable behavior and prevent system-wide blackouts. Several control schemes sense the loss of major transmission lines and initiate switching of corrective equipment. A limitation of many control schemes is that the scheme does not sense local conditions and track the evolution of the disturbance. Without local sensing, switching actions can generate abnormal voltages, which could damage expensive high-voltage compensating equipment.

The COTP Controller described in this paper corrects many inadequate features of power system control schemes. The controller senses local substation bus voltages and makes intelligent decisions during periods of power system emergencies. Advanced voltage transducers, programmable logic controllers, and fast communications protocols are used. Future work will report on how the instrumentation has performed. One motivation for using modern technology was to provide practicing engineers with continuing education.

I. Introduction

Modern power systems are one of the largest, most complicated systems developed by humans. With interconnections to neighboring utilities, a power grid may cover several states and provinces. In Western North America, the power grid serves all or parts of fourteen states of the US, two Canadian provinces, and portions of Baja California, Mexico. This interconnected system is commonly called the Western Systems Coordinating Council (WSCC).

Electrical energy is exchanged between the Pacific Northwest of the US and northern California primarily on three 525 kV AC transmission lines and one +/- 500 kV DC line. The instrumentation described is being installed at two substations of the 525 kV California-Oregon Transmission Project (COTP). When commissioned in 1993, this transmission line provided the third 500 kV interconnection between the Pacific Northwest and northern California.

The COTP line runs roughly 340 miles from the Captain Jack Substation in southern Oregon to the Tracy Substation, near Tracy, California, east of San Francisco. The instrumentation described here is installed at Olinda Substation, near Redding, CA and Tracy Substation. The COTP line, along with the other AC and DC lines, provides up to 7900 megawatts (MW) of electrical transmission capacity between the Northwest and California. This transmission capacity provides a great economic benefit for to the western US. Electrical energy can be exchanged between the Pacific Northwest and California. In the summertime when California loads are at their highest, the Northwest can provide power from their large hydroelectric generation capacity. Conversely, in the winter when the Northwest loads peak, California loads are fairly low and therefore excess generation can be provided to the Northwest.

Power systems occasionally have local outages caused by lightning, tree branches, and other causes. More rarely, systems can have wide-scale global problems, such as instability. Unforseen third or fourth order contingencies can occur and, if not managed, lead to power system blackouts, such as happened in 1996 [1,2]. Specific stability problems can be solved with specific discrete supplementary controls [3]. When one or more of the AC or the DC transmission lines connecting the Pacific Northwest and California are lost, electrical energy flows on the remaining electric paths and overloads these paths. When AC transmission lines are overloaded, the voltage on the lines and at major substations starts to decrease [4]. Conversely, if transmission lines connecting central California with southern California are out of service, too much electrical power is flowing in and has no where to go. In this scenario, the voltage on lines and at substations rises to dangerously high levels. An intelligent control scheme must take measures to lower the high voltage before costly equipment is damaged.

During power system emergencies, blackouts may be prevented if compensating equipment located at major substations can be quickly energized or de-energized. The compensating equipment consists of high-voltage capacitors (which raise voltage) or inductors (which lower voltage) connected between the high-voltage system and ground. A connection between the transmission line and ground is called a shunt connection.

Several California utilities have worked together to install a control scheme called the Remedial Action Scheme (RAS). RAS senses the loss of one or more of the major transmission lines in northern California [5]. When a major disturbance is in progress, the RAS scheme (located in San Francisco, CA) sends a signal to all substations where mitigating actions need to happen. Under emergency conditions where the voltage is falling, the existing RAS calls for many control actions throughout California, including the switching on and off of high voltage compensating equipment. Voltage decline can be arrested if shunt-connected inductors are removed from service and shunt-connected capacitors are energized. However, if all shunt inductors are de-energized and all capacitors are energized at the same time, the local substation voltage may jump above equipment design limits.

As described in following sections, the COTP Controller will measure voltages at the substation and control equipment switching. One problem with the existing RAS was the scheme could ask for actions that were good for the bulk transmission system, but could damage expensive power system equipment. The controller described in this paper will monitor the local substation bus voltage and will energize or de-energize high-voltage compensation equipment to benefit the overall power system, but not damage local equipment.

Electric power has been a regulated monopoly and a reliability orientated industry. The industry has been slow to adopt new methods. Traditionally a control project like this would have been realized in a large number of "hard" wire connections between discrete control relays. Such control design is expensive and hard to modify. The idea of using PLCs was sold to management as a means to save money now and new modifications.

A equally important reason for using modern technology was employee continuing education. Continuing education of practicing engineers and technicians is difficult due to remoteness from formal education centers, limited time for training on the job, and institutional inertia. This project was supported by management as a way to help employees stay current. Since the project was started, the first author was transferred to the agency training center where he intends to use the knowledge gained in the project in future classroom work.

Researchers at the Canadian provincial power authority for Quebec, Hydro-Quebec, have constructed a control system that includes the switching of 735 kV shunt inductors [6]. The control scheme has the French acronym of MAIS. MAIS and the COTP Controller are similar, but have important differences. Each MAIS installation can trip or close shunt inductors independent of an external signal. The COTP Controller, for an overvoltage protection function, only operates when the external global RAS signal is received. The two schemes both measure voltages, initiate switching actions, measure the voltage again, and can initiate additional switching actions. Other similarities and differences exist.

II. Design Considerations

The design requirements for a controller included reliability, flexibility, economical, and adaptability. Any controller must be reliable because the controller must take the correct actions during times of power system emergencies. Operating experience may require changes in settings and control constants, hence the controller must be flexible and easy to change. Electrical power utilities are being reorganized and streamlined. All costs must be minimized. These factors pointed to the use of modern transducers and programmable logic controllers (-PLCs).

Many hundreds of computer simulations of the operating characteristics of the western US power system have been performed. These simulations were studied and a control strategy was developed. Four tables of desired control actions were developed for Olinda and Tracy Substations, for the two possible requested RAS control actions [7]. Table 1.shows the design requirements for Olinda Substation and case where the global condition where the RAS calls for a voltage increase. The three other tables are similar in form.

Olinda Bus Voltage (kV)	Equipment in Service	Actions
Below 505	Any substation configuration.	Trip all (two) shunt reactors & energize the one shunt capacitor with or without RAS.
Below 518	Two shunt reactors.	Trip both reactors.
	One shunt reactor.	Trip the reactor, energize the capacitor.
	No reactors.	Energize the capacitor
	*One reactor, one capacitor (abnormal operation).	Trip the reactor, the capacitor stays energized.
	No reactors, one capacitor.	No change, the capacitor stays energized.
Below 527	Two shunt reactors.	Trip one reactor.
	One shunt reactor.	Trip one reactor.
	No reactors.	Energize the capacitor.
	*One reactor, one capacitor.	Trip the reactor, the capacitor stays energized.
	No reactors, one capacitor.	No change, the capacitor stays energized.
Above 527 (or equal to)	Any reasonable substation configuration.	No action.

* denotes abnormal operation.

Table 1. Olinda Substation, Caps In, Reactors Out

Even with hundreds of simulations, the nature of most major power system disturbances is not entirely predictable. The disturbance may evolve along different paths over time, each path calling for different actions for the controller described here. A major strength of this controller is its ability to execute a programming loop and make more decisions as the disturbance progresses. It was decided to initially use three different sensing times:

1. immediately upon receipt of a RAS signal execute the above control actions,
2. thirty electrical cycles (0.5 s) later, measure the voltage and execute the control actions,
3. thirty seconds later do the same as 2.

The controller will only act upon Numbers 2 and 3 above if the RAS signal persists. These times were implemented as PLC timers and can be easily modified in the future

The issues of transducer and controller response time were addressed. The PLC operates in milliseconds, an adequate speed for power system applications where times are measured in cycles (16.7 ms in 60 Hz. systems). Typical voltage transducers have response times in the hundreds of milliseconds, if not 0.5 second, which was too slow for this application. Equipment research found a transducer, which has a response delay of roughly 125 milliseconds and the resolution is 128 samples per cycle. The next generation of transducers may have a response time of roughly 50 milliseconds (and have positive, negative, and zero sequence components).

Studies of the transient response of the power system showed there were no problems if the shunt inductor(s) and energize the shunt capacitors were switched at the same time. Switching studies using the ElectroMagnetics Transients Program (EMTP) showed there was no need to wait a few milliseconds after tripping the inductors before closing the capacitors and conversely. This initially sounds counterproductive with one devise boosting the voltage while the other bucks the voltage. This is done for speed. The power system cannot wait for the inductor to be tripped during a major disturbance.

III. Instrumentation

There are two controller schemes operating in parallel for reliability. A block diagram for one of the redundant schemes is shown in Figure 1. Each scheme consists of one three-phase

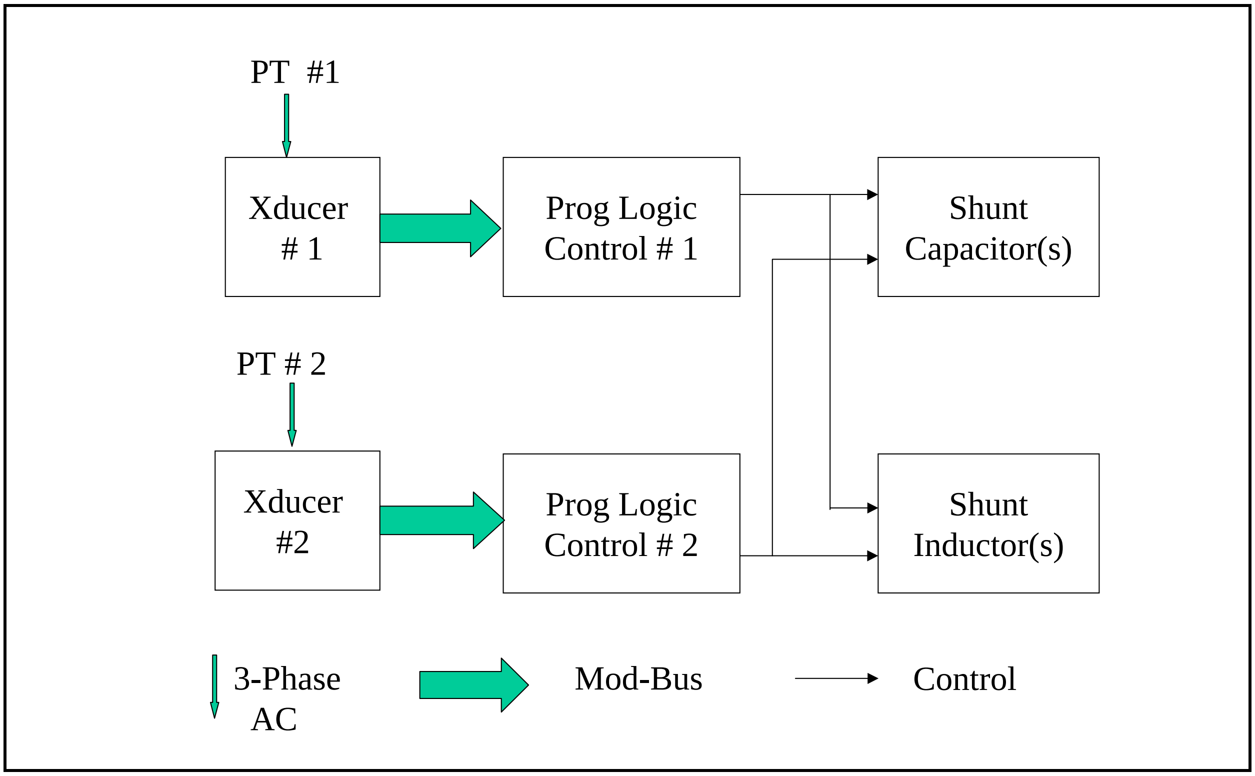

Figure 1. Block Diagram of COTP Controller

transducer, one compact programmable logic controller (PLC), and interposing relays. The transducer is used to provide voltage input to the PLC via Modbus Plus communications. The PLC is programmed to provide local substation bus voltage supervision to the RAS signal. The programming software used for the PLC is Modsoft. The interposing relays are used to provide the PLC with an adequate contact rating to perform switching of the compensation devices.

The transducer for each scheme is connected to a separate high-voltage bus potential transformer winding for reliability purposes. The output signal of the transducer is connected to the PLC via a Modbus Plus cable. The PLC consists of one 16 MHZ CPU, two 125 VDC power supplies (one power supply for the CPU and the other one is for the I/O modules), and five 8IN/4OUT I/O modules. The transducer has a response time roughly 125 milliseconds and the resolution is 128 samples per cycle.

IV. Programming

The PLC is programmed to provide adequate voltage compensation when the local bus is within the predetermined voltage bands and reception of a RAS signal. The voltage band is determined by the system studies. It is programmed to block operation for any fault conditions causing single phase or three phases voltage drops below 0.65 per unit. If there are gross overvoltage or gross undervoltage conditions at the local substation, without any signal from RAS, the PLC will energize or de-energize the appropriate compensation equipment to provide local voltage compensation. The program also restricts the shunt equipment breakers from closing more than once within two minutes for equipment protection. For system operation and troubleshooting, the PLC is programed to alarm. It alarms when a RAS signal comes in regardless of whether the voltage is within or not within the voltage bands. When the controller scheme losses power or equipment fails the PLC will alarm.

The PLC obtains the local substation three phase-to-neutral bus voltages from the transducer and arithmetically averages the voltages. The PLC then compares the average voltage with the predetermined voltage bands during each scan. There are three different RAS signals the PLC receives from Pacific Gas & Electric Company (PG&E): Capacitor IN and Reactor OUT, Reactor IN and Capacitor OUT, and Capacitor OUT. Once a RAS signal is received, the PLC latches the signal for 31 Seconds. Within the 31-second interval, the program sets up three loops to check whether the local bus voltage is within the voltage bands. The first loop is set up to check the voltage upon reception of a RAS signal. If the bus voltage is within the voltage bands, the PLC will perform the preprogramed action, otherwise do nothing. The second loop is set up to perform the same logic three cycles (50 milliseconds) after the first loop. The third loop is set up to perform the same logic again 30 seconds after the second loop.

IV. Conclusions

Many recent events have shown the dependence of modern society on reliable electrical energy. Modern power systems are vast collections of generators, transmission lines, transformers, and distribution systems. The control of this large system is a very challenging task. This paper has discussed an enhancement to a remedial action control scheme in use in the state of California. Redundant voltage transducers and programmable logic controllers were used to measure local substation voltages and make intelligent control decisions. The controller is programmed to place the need of the high-voltage bulk power system against the health of expensive substation equipment. Instrumentation and programming were described which will accomplish this sensitive and critical requirement.

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Biographies:

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