Toward a Self-Healing Protection and Control System

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***Abstract*—This paper first presents a review of the current technology in power system protection and control, including the protective relays, local controls and system controls. Then, this paper presents a couple of typical scenarios to illustrate the possible problems with the existing technology. Next, this paper proposes the vision of a self-healing protection and control system based on real-time, look-ahead simulation such as in every 5 to 15 minutes. This is different from the present technology such as Special Protection Scheme, which is based on a large amount of offline simulation runs. Last, challenges and technology gaps to implement the proposed idea are discussed.**

***Index Terms*—Self-healing, power system protection, power system control**

I. Introduction

THE present technology in power system protection and control has been considered unsatisfactory to provide a robust, fast, and efficient support to system-wide disturbance. On one hand, the present protection and control systems consist of many devices across the system and they lack a system-wide coordination scheme. This sometimes can worsen the system conditions during emergency. On the other hand, settings of protection devices and parameters of control systems are pre-determined based on off-line simulation results and remain fixed regardless of system operating conditions.

The latest development in communication, control and computing systems has attracted increasing interests in power engineering community to explore possible solutions to build more robust power systems [1-2]. Such systems should be able to fully utilize the real-time, system-wide information, dynamically adjust the protection and control, and effectively restore the system to normal conditions. With this vision, the concept of a self-healing protection and control system is proposed and discussed in this paper. Different from the previous discussions in [1-2], this paper presents a more detailed approach about a possible implementation of a self-healing protection and control system.

This paper is organized as follows. Section II reviews the present technology of protective relays, local controls and system controls. Section III presents the possible problems with the present protection and control with two cases. Section IV presents the idea of self-healing protection and control and discusses the potential challenges and technology gaps to implement it. Section V concludes the paper.

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II. Technical Review of the Present Protection and Control Systems

This section provides a review of the present technology in power system protection and control in the literature [3-9]. Here, the present technology is classified as protective relay, local control, and centralized control for illustrative purposes. Certainly, other classifications may be appropriate based on different viewpoints.

A. Protective Relay

Distance relaying

Distance relay is the mostly commonly used relay for transmission line protection. Distance relays measure voltage and current and also compare the apparent impedance with relay setting. When the tripping criteria are reached, distance relays will trip the breakers and clear the fault. Typical forms of distance relays include impedance relay, mho relay, modified mho relay, and combinations thereof. Usually, distance relays may have Zone 1, Zone 2 and Zone 3 relays to cover longer distances of transmission lines with delayed response time as shown below:

- Zone 1 relay time and the circuit breaker response time may be just 2-3 cycles
- Zone 2 relay response time is typically 0.3-0.5 seconds
- Zone 3 relay response time is about 2 seconds.

Figure 1 shows the Zone 1, Zone 2 and Zone 3 distance relay characteristics.

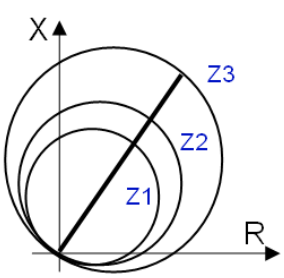

Fig. 1: R-X diagram of Zone 1, Zone 2 and Zone 3 Distance Relay Characteristics.

Out-of-step (OOS) relaying

OOS relaying provides blocking or tripping functions to separate the system when loss of synchronism does occur. Ideally, the system should be separated at such points as to maintain a balance between load and generation in each separated area. Moreover, separation should be performed quickly and automatically in order to minimize the disturbance to the system and to maintain maximum service continuity via OOS blocking relay and tripping relay.

During a transient swing, the OOS condition can be detected by using two relays having vertical (or circular) characteristics on an R-X plane as shown in Fig. 2. If the time required to cross the two characteristics (OOS1 and OOS2) of the apparent impedance locus exceeds a specified values, the OOS function is initiated. Otherwise, the disturbance will be identified as a line fault. The OOS tripping relays should not operate for stable swings. They must detect all unstable swings and must be set so that normal load conditions are not picked up. The OOS blocking relays must detect the condition before the line protection operates. To ensure that line relaying is not blocked for fault conditions, the setting of the relays must be such that normal load conditions are not in the blocking area.

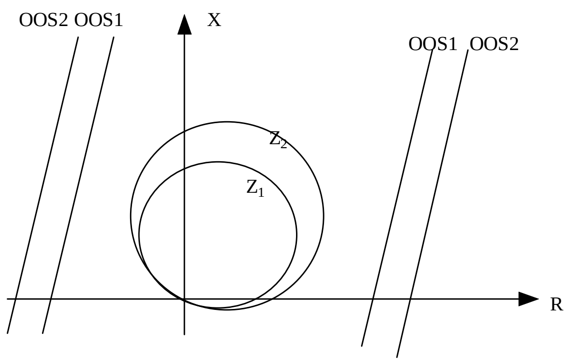

Fig. 2: Tripping zones and out-of-step relay.

B. *Local Control*

Prime Mover Control and Automatic Generation Control (AGC)

The prime mover control and AGC are applied to maintain the power system frequency within a required range by the control of the active power output of a generator. Prime movers of a synchronous generator can be either hydraulic turbines or steam turbines. The control of prime movers is based on the frequency deviation and load characteristics. The Automatic Generation Control (AGC) is used to restore the frequency and the tie-line flow to their original and scheduled values. The input signal of AGC is called Area Control Error (ACE), which is the sum of the tie-line flow deviation and the frequency deviation multiplied by a frequency-bias factor.

Power System Stabilizer (PSS)

PSS technology is to improve small signal stability or improve damping. PSSs are installed in excitation system to provide auxiliary signals to the excitation system voltage regulating loop. The input signals of PSSs are usually signals that can reflect the oscillation characteristics, such as the shaft speed, terminal frequency and power.

Excitation

Generator excitation system is to improve power system stability and power transfer capability, which are the most important issues in bulk power systems under heavy load flow. The primary task of the excitation system in synchronous generators is to maintain the terminal voltage of the generator at a constant level and guarantee reliable machine operations in all operating points, which achieves the governing functions of (1) voltage control; (2) reactive power control; (3) power factor control with excitation current limitation, stator current limitation and rotor displacement angle limitation linked to governor.

On-Load Tap Changer (OLTC)

OLTC is applied to keep the voltage on the low voltage (LV) side of power transformer within a preset dead band such that the power supplied to voltage sensitive loads is restored to the pre-disturbance level. Usually, OLTC takes tens of seconds to minutes to respond to the low voltage event. OLTC may have a negative impact to voltage stability because higher voltage at the load side may demand higher reactive current to worsen the reactive problem during a voltage instability event.

Shunt Compensation

The shunt compensators in bulk power systems include traditional technology like capacitor banks and new technologies like Static Var Compensator (SVC) and STATic COMpensator (STATCOM). SVC consists of shunt capacitors and reactors connected via thyristors that operate as power electronics switches. They can consume or produce reactive power at speeds in the order of milliseconds. One main disadvantage of the SVCs is that their reactive power output varies according to the square of the voltage they are connected to, similar to capacitors. STATCOM are power electronics based SVCs. They use gate turn off thyristors or Insulated Gate Bipolar Transistors (IGBT) to convert a DC voltage input to an AC signal chopped into pulses that are recombined to correct phase angle between voltage and current. STATCOMS have a response time in the order of microseconds.

Load shedding

Load shedding is performed only under the extreme emergency, such as faults, loss of generation, switching errors, lightning strikes, and so on, in modern electric power system operation. For example, when system frequency drops due to the insufficient generation under a large system disturbance, load shedding should be done to bring frequency back to normal. Also, if bus voltage slides down due to insufficiency of reactive power, load shedding should also be performed to bring voltage back to normal. The formal load shedding scheme can be realized via under-frequency load shedding (UFLS) while the latter scheme can be realized via under-voltage load shedding (UVLS).

C. *Centralized Control*

SCADA/EMS

SCADA/EMS is the most typical application of centralized control in power systems. It is a hardware and software system used by operators to monitor, control and optimize a power system. The monitor and control functions are known as SCADA; the advanced analytical functions such as state estimation, contingency analysis, and optimization are often referred to as EMS. Typical benefits of SCADA/EMS systems include: improved quality of supply; improved system reliability; and better asset utilization and allocation.

An increasing interest in the EMS is the online security analysis software tools, which typically provide transient stability analysis, voltage security analysis, and small-signal stability analysis. The latest development in computer hardware and software and power system simulation algorithms has present more accurate results for these functions in real-time, which could not be achieved online in the past.

Special Protection Systems (SPS)

SPS is also known as Remedial action schemes (RAS) or system integrity protection systems (SIPS). SPS has become more widely used in recent years to provide protection for power systems against problems not directly involving specific equipment fault protection. SPS is applied to solve single and credible multiple contingency problems. These schemes have become more common primarily because they are less costly and quicker to permit, design, and build than other alternatives such as constructing major transmission lines and power plants.

SPS senses abnormal system conditions and (often) takes pre-determined or pre-designed action to prevent those conditions from escalating into major system disturbances. SPS actions minimize equipment damage and prevent cascading outages, uncontrolled loss of generation, and interruptions to customer electric service. SPS remedial actions may be initiated by critical system conditions which can be system parameter changes, events, responses, or a combination of them. SPS remedial actions include generation rejection, load shedding, controlling reactive units or/and using braking resistors.

D. *Time Delay of different protection and control*

Figure 3 summarizes the time delay in logarithm of various protection and controls based on a number of literatures [3-9].

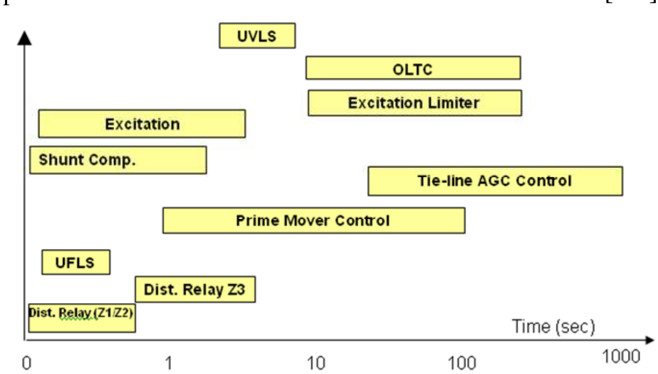

Fig. 3. Time delay of various protection and controls

III. Examples of Possible Problems of the Present Technology

A. *Case I: Load Shedding or Generator Tripping*

Figure 4 is a show case of possible coordination problem when a two-area system is experiencing a load increase in the load pocket (the right area in Fig. 4). When this happens, both frequency and voltage decrease. If this load continues to increase, perhaps with some simultaneous contingency event, it may be beyond the capability that the system can handle. Then, it certainly needs to shed load in the load pocket.

However, there may be a problem if the generators' under-frequency (UF) tripping scheme and the loads' under-voltage (UV) shedding scheme are not well coordinated. Likely, the under-frequency generation tripping scheme will disconnect some generation from the system before the load shedding actions, since the present setting in generation tripping is very fast. This will worsen the imbalance between load and generation. Hence, both voltage and frequency will decrease further. This may lead to more generation to be quickly tripped to cause a sharp drop of voltage and eventually a fast voltage collapse at the end. Therefore, even though this is initially a frequency stability problem, the final consequence is a voltage collapse. Figure 5 shows the gradual process based on the above analysis.

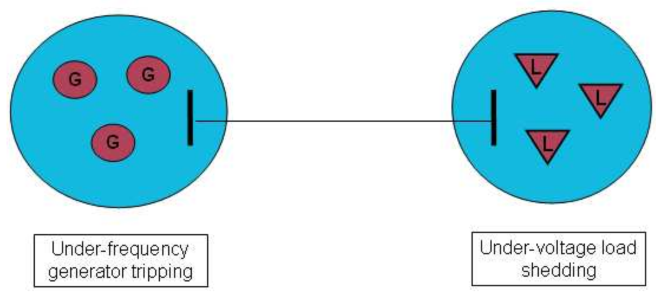

Fig. 4. A two-area case after disturbance.

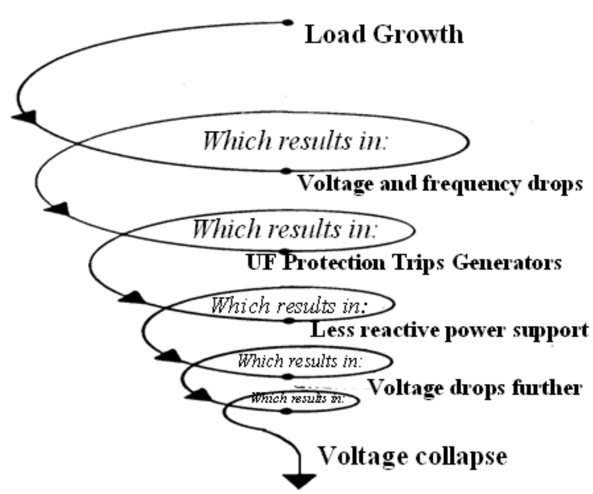

Fig. 5. The process of the instability problem.

A possible solution to the above problem is to develop a fast and efficient approach to dynamically analyze the system state in real-time or in 5-minute look-head mode. The new process can be described as follows:

- The system is moving towards voltage stability limit.
- Generator UF tripping should be temporarily adjusted with longer delays.
- Preventive control strategies should be immediately implemented such as increasing reactive power output of generator, switch shunt compensators, etc.
- Load shedding should be activated (or a warning is given to load shedding device).
- If the load continues to grow and pass over the security limit, load at some critical substations will be shed immediately.
- If the load decreases and the system moves back to a secure state, the generator protection will be re-set to original values, and the planned load shedding should be cancelled.

B. Case II: Zone 3 Protection

This second example is from the July 2, 1996 WSCC blackout [8-9]. At the very beginning of the blackout, two parallel lines were tripped due to fault and mis-operation, and consequently some generation was tripped as a correct SPS response. Then, a third line was disconnected due to bad connectors in a distance relay. After about 20 seconds of these events occurred the last straw of the collapse, which was the trip of Mill Creek - Antelope line due to the undesired Zone 3 protective relay. The relay did what it should do based on its Zone 3 setting, which is to trip the line when the observed apparent impedance encroached the circle of Zone 3 relay. In this case, the low apparent impedance was the consequence of the power system conditions at that moment.

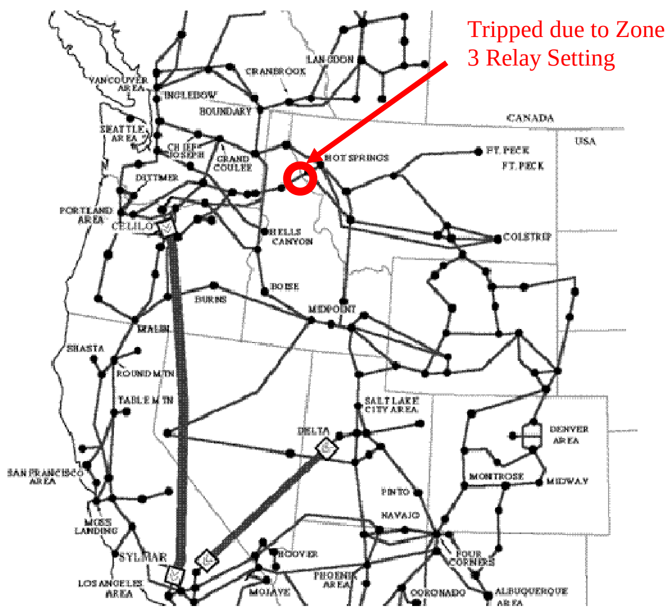

Fig. 6. WSCC July 2, 1996 Blackout

Apparently, the above problem may be avoided if the Zone 3 setting can be dynamically adjusted based on the system condition from real-time simulation. This can be briefly summarized as follows.

- If the system loses one or more lines, this may lead to a high power flow at other lines.
- The Zone 3 relay settings of those high power flow lines should be examined using the post contingency power flow analysis results.
- The Zone 3 protections shall be immediately adjusted or blocked to avoid tripping. This gives time to other protection and control (such as load tripping) to handle the contingency event.

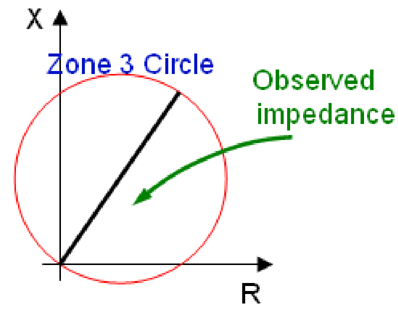

Fig. 7. Observed impedance encroaching the Zone 3 circle.

IV. Vision of Future Self-Healing Protection and Control Systems

From the previous two case studies, we propose the following vision of a future Self-Healing Protection and Control System, as shown in Figure 8.

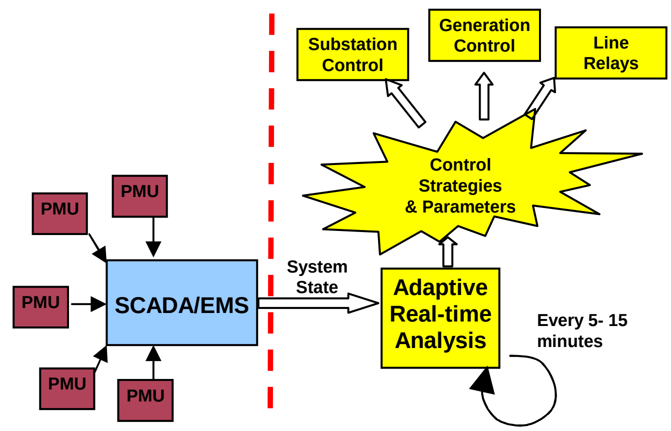

Fig. 8. The proposed self-healing protection and control system.

In Fig. 8, the SCADA/EMS system collects data from Phasor Measurement Units (PMU) due to the expected success and large-scale deployment in the near future. Then, the EMS system will give an estimation of the present system state. As shown in the left part in Figure 8, this is similar to the present technology.

The difference is the new function shown in the right part in Figure 8, where an adaptive real-time or look-ahead analysis shall be performed every 5 to 15 minutes. The analysis will give some recommendation of possible updated control strategies and parameters, especially in the event of contingencies. That is, the system shall know what actions to take based on the present system condition in the case that a certain contingency does occur in the next 5 or 15 minutes.

The possible action could be whether Zone 3 backup relays should be adjusted based on the present system condition or not, load shedding should be activated to enter a warning state or not, etc. Certainly, the updated strategy and parameters shall be delivered to the remote protective device and control systems. Therefore, if a contingency really occurs in the next 5 or 15 minutes, different remote local controls should know what actions to take, and these actions should be a coordinated action based on the real-time or look-ahead simulation.

Apparently, there exist many technical gaps to implement the proposed self-healing protection and control systems. Several challenges are summarized as follows:

- There is a lack of online coordination schemes of different protection and controls. The present technology like SPS is based on a large amount of offline studies, while the proposed work requires a fast, robust approach to coordinate the controls in real time.
- The present technology is mainly controlled by local signals, while the proposed work requires the protective relay to respond to extensive, adaptive system signals.
- The present EMS system has a state estimation function based on data collected from Remote Terminal Units (RTU), while the future EMS system may have a real-time synchronized state measurement to have better accuracy and speed.
- The present communication infrastructure is a mix of telephone lines, Broadband over Power Lines (BPL), wireless communication, microwave, optical fiber, and so on, while the future communication infrastructure should be fast, dedicated communication system like optical fiber such that the communication delay will be minimized. Also, communication protocol standard and Quality of Service (QoS) should be fully implemented.
- The present computing technology in most control centers is based on sequential computing, while the future work may be based on dedicated parallel computing resources with proper prioritizing and scheduling of different real-time simulation tasks

V. Conclusions

This paper first presents a brief review of the present technology of power system protection and control. Then, discussions are presented to illustrate the possible problem and inefficiency with the present technology. The vision of a potential solution, called self-healing protection and control, is proposed with discussions about the major technology gap to overcome in order to fully implement the proposed idea in the long run. Future work may lie in research and demonstration of the feasibility of the proposed concept of self-healing protection and control.

VI. Acknowledgment

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VIII. Biographies

Fangxing (Fran) Li (M’01, SM’05) received the B.S. and M.S. degrees in electrical engineering from Southeast University, Nanjing, China, in 1994 and 1997, respectively. He received the Ph.D. degree from Virginia Tech in 2001. He has been an Assistant Professor at The University of Tennessee (UT), Knoxville, TN, USA, since August 2005. Prior to joining UT, he was a principal R&D engineer at ABB Electrical System Consulting (ESC). His current interests include distributed energy resources, power markets, protection and control, reactive power, and reliability. He is the recipient of 2006 Eta Kappa Nu Outstanding Teacher Award at UT, voted by undergraduate ECE students. Dr. Li is a registered Professional Engineer (PE) in the state of North Carolina.

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