MAXIMIZING POWER SYSTEM STABILITY THROUGH WIDE AREA PROTECTION

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Abstract: This paper describes basic principles and purpose for applying wide area protection schemes, also known as Remedial Action Schemes (RAS) or System Protection Schemes (SPS). In the areas of power system automation and substation automation, there are two different trends: centralization and decentralization. More and more dynamic functions are moving from local and regional control centers towards central or national control centers. At the same time we also observe more "intelligence" and "decision-power" moving closer towards the actual power system substations. Greater functional integration is being enclosed in substation hardware. This raises discussions concerning reliability (security and dependability). The main targets for this paper are to:

- Sort out the terminology used in this area;
- Describe different application areas and related requirements;
- Illustrate different design principles – "top-down", "bottom-up", hierarchy, flat, etc., for different applications;
- Identify similarities and differences between classic equipment protection and system protection –concerning philosophy as well as concerning product and system design; and
- Show the value of wide area protection.
- Illustrate the great breakthrough for wide area protection, since the introduction of synchronized phasor measurements, based on PMUs (Phasor Measurement Units).

I. BACKGROUND AND INTRODUCTION

There are a few basic facts and technological developments that have pushed the utility needs and the suppliers' offers in wide area protection and control:

1) The de-regulated electricity market cause rather quick changes in the operational conditions. New, unknown, load flow patterns show up more frequently for the system operator.
2) Economic pressure on the electricity market and on grid operators forces them to maximize the utilization of the high voltage equipment, which very often means operation closer to the limits of the system and its components. For the same reason there is also a wish to "push" the limits.
3) Reliable electricity supply is continually becoming more and more essential for the society and blackouts like Northeast 8/14 are becoming more and more costly whenever they occur.
4) Technical developments in communication technology and measurement synchronization have made the design of system wide protection solutions possible. The

use of phasors, measured by PMUs, also provides new possibilities for state estimator functions. Their main use so far has been for WAMS (Wide Area Measurement System) applications.

5) There is a general trend to include both normal operation issues and disturbance handling into power system automation.
6) Wide area disturbances during the last decades have forced/encouraged power companies to design system protection schemes to counteract voltage instability, angular instability, frequency instability, to improve damping properties, or for other specific purposes, e.g. to avoid cascaded line trip.
7) Research and development within universities and industry have significantly increased knowledge about the power system phenomena causing widespread blackouts. Methods to counteract them have been or are being developed, e.g. [1, 2].

II. MARKET DEMANDS AND UTILITY NEEDS

Based on the operating situation and new technology described above, grid companies can benefit significantly. Wide area protection and emergency control systems can be introduced in the power system,

- to increase the power system transmission capability, and/or
- to increase the power system reliability.

This means that the grid company can extend the system operational limits, i.e. operate the system closer to the natural constraints, maximizing return on investments in high voltage equipment. The operational criteria will change from

- "the power system should withstand the most severe credible contingency", to
- "the power system should withstand the most severe credible contingency, followed by protective actions from the wide area protection system".

Certain power systems do not fulfill the design and operational criteria, which are based on the reliability requirements on the system, without installation of wide area protection systems. The reliability requirements on such wide area protection systems – dependability as well as security – are extremely high.

2.1 How to meet Present and Future Demands?

Utility companies may require one package for the entire operation of the power system, including planning, operation, control, and protection – optimized on a "system" level, based on maximum profit and supply reliability. This "package" should consist of a number of integrated, product offerings and should be compatible with present equipment. This approach benefits both retrofit and new installations. To allow for retrofit, such a package should use present technology and move towards standardized communication, standard input and output format, etc.

Large utilities, such as Hydro Québec, BC Hydro, and BPA, still design their own system protection schemes and defense plans, based on standard components available today. To make the area of system protection available also for other utilities there is a market need for dedicated system protection devices and basic system protection design structures. Such systems could be based on standardized system protection terminals, with customized functionality, tied together in a wide area protection system. Standardization, modularization and flexibility are important features in such a design.

III. TERMINOLOGY

Protection is very closely related to circuit-breaker trip signals to disconnect faulty or overloaded equipment from the network, to save the component, and to re-establish normal operation of the healthy part of the power system and thereby continue electricity supply to utilities. Protection equipment is also aimed at protecting people, animals and property from injury and damage due to electric faults. The situation when a protection device triggers, is so severe that if the equipment is not tripped, it will be severely damaged or the surrounding will be exposed to serious danger.

System protection or *wide area protection* is used to save the system from partial or total blackout or brown-out in operational situations when no particular equipment is faulted or operated outside its limitations. This situation could appear after the clearance of a very severe disturbance in a stressed operation situation or after extreme load growth. Since it is a protection system it will operate in such operational situations when the power system would break down if no protective actions were taken. Such protective actions also comprise shift of setting groups and parameter values for different protection and control devices, blocking of LTCs, switch in of shunt capacitors, etc.

Emergency control is associated with continuous control actions in order to save the power system, such as boosting the exciter on a synchronous generator or changing the power direction of an HVDC link.

Protection, system protection and emergency control comprise ***corrective*** (or curative) measures, i.e. actions are really needed to save the component or the system.

Normal control actions are associated with continuous control activities, that can be either step-wise, e.g. tap-changer and shunt device, or continuous, such as frequency control. Normal control is *preventive*, i.e. actions are taken to adjust the power system operational conditions to the present and near future expected situation. Normal control is usually automatic, e.g. tap-changer, reactive shunt device, frequency control and AGC.

SCADA/EMS functions are tools that assist the power system / grid operator in his effort to optimize the power system operation, with respect to economy, operational security and robustness, as well as human and material safety. Actions are normally (at least supposed to be) ***preventive***, i.e. actions taken to adjust the power system operational conditions to the present and near future anticipated situation. Preventive actions, based on simple criteria, can beneficially be implemented in SCADA/EMS and be performed automatically or be suggested and then released or blocked by the operator. SCADA/EMS systems are normally too slow to capture power system dynamics.

Phasor Measurement Units (PMU), is a device for synchronized measurement of AC voltages and currents, with a common time (angle) reference. The most common time reference is the GPS-signal, which has a precision down to 1 μs. In this way the AC quantities can be measured as complex values and represented by their magnitude and phase angle to deal with complex system events.

IV. POWER SYSTEM PHENOMENA TO COUNTERACT

Utility needs and problems are often formulated in very loose terms, such as “intelligent load shedding”, “protection system against major disturbances”, and “counteract cascaded line tripping”. These needs have to be broken down to physical phenomena, such as protection against:

- Transient angle instability (first swing)
- Small signal angle instability (damping)
- Frequency instability
- Short-term voltage instability
- Long-term voltage instability
- Cascading outages

4.1 TRANSIENT ANGLE INSTABILITY

Off-line design studies have normally been made to ensure the transient angle stability for credible contingencies. Parameters required during the design stage, are line circuit impedance, trip time, autoreclosing, inertia constants, and additional equipment such as series capacitors and breaking resistors. In the operational stage certain power flow levels must not be exceeded. PMUs allow for direct and fast angle measurement, instead of indirect power measurement, and more accurate control algorithms for emergency control or protective actions can be designed.

4.2 SMALL SIGNAL ANGLE INSTABILITY

Off-line studies, such as eigenfrequency analysis and time simulations, have to be done to check the damping conditions for different frequencies. Static Var Compansators (SVCs) in the network and power system stabilizers on the generators are common means to counteract power oscillations. Again PMUs in the power system can provide accurate angle measurements.

4.3 FREQUENCY INSTABILITY

Frequency instability is most commonly the result of a sudden, large generation deficit. Automatic underfrequency controlled load shedding is the widely used measure to counteract a system breakdown in such situations. Also the time-derivative of the frequency is used in some applications. In case of overfrequency, due to sudden loss of load, generators can be shed.

4.4 SHORT-TERM VOLTAGE INSTABILITY

Short term voltage instability is normally associated with an extremely severe reduction of the network capacity, e.g. caused by the trip of several parallel lines due to a bush fire. Characteristic for the short-term voltage instability is that there is no stable equilibrium point immediately after the clearance of the initial fault(s). Remedial actions to save the system in such a situation therefore have to be fast (a few seconds or fractions of a second) and powerful (e.g. large amount of load shedding).

4.5 LONG-TERM VOLTAGE INSTABILITY

When a power system is in transition towards a “long-term voltage instability”, the power system “survived” the initial disturbance, i.e. there was a stable equilibrium point immediately after the clearance of the disturbance. However, load recovery and tap-changer operation cause the transmission system voltage to decrease and the collapse occurs in the time-scale of 10 seconds to 30 minutes. Without any initial disturbance, a long-term voltage instability might occur due to a very large and rapid load increase.

4.6 CASCADING OUTAGES

Cascading outages of lines or generators might have different origins, but are mainly associated with some kind of overload, followed by trip of one line or generator unit, which cause an increased overload on the remaining units, and so on. In such situations load shedding or generation rejection might be required to preserve the integrity of the power system.

For each phenomenon a reliable (based on redundancy and robustness) protection system has to be designed, with respect to input variables, decision criteria and output actions. Parallel systems counteracting different phenomena and different layers of safety nets can be designed and coordinated.

V. NORMAL VS. EMERGENCY CONTROL

The difference between *normal* and *emergency* control is the consequence for the power system if the control action is not performed. If a normal, *preventive*, control action is not performed there is risk for the loss of power system stability, i.e. stability will be lost if a severe disturbance occurs. If an emergency, *corrective*, control action is not performed, the system will go unstable. The response requirements (time and reliability) are normally higher for emergency control actions than for normal control actions. Emergency control functions are almost always automatic, while normal control actions can be either automatic or manual, e.g. in conjunction with alarms. The actions taken in the power system are however quite similar for both normal control and emergency control.

Voltage control
Voltage control comprises actions like AVR, tap-changer, and shunt device, automatic or manual control. The control variable is usually the voltage level or reactive power flow. For system protection purposes or "emergency control" also load shedding and AGC can be used.

Frequency control
Primary frequency control is normally performed in the power stations by governor controls, while secondary frequency control is performed by AGC change of set-point or start/stop of units by the dispatcher. For emergency control, load shedding as well as actions that reduces the voltage and hence the voltage sensitive part of the load, can be used.

Power flow control
Load level, network topology and generation dispatch are the most common parameters that influence the power flow. Automatic power flow control is performed by AGC, HVDC-control, UPFC, TCSC, phase-shift transformers, etc.

Angle control
Angle control is more accurate if based on PMUs. Without PMUs power flow is an indirect method of measuring and controlling the angle. The actions are similar as for power flow control.

VI. REQUIREMENTS ON PROTECTION COMPARED TO SCADA/EMS

Products for wide area protection and emergency control should be designed and manufactured in a similar way as conventional equipment protection, concerning standardization, flexibility, hardware and software modularization, configuration and functionality. Maximum benefit from

available hardware that have passed different kinds of EMC and environmental tests, as well as, software functions available from other protection terminals, has to be made. Standardized communication protocols and hardware are also essential. The value of measurement accuracy is discussed in Appendix 1.

SCADA/EMS functions based on phasor measurements and inputs from system protection terminals should in general be compatible with present and future SCADA/EMS systems.

Based on synchronized phasor measurements, more efficient state estimation can be performed. Based on fast and reliable state estimation a variety of system stability indices can be derived and monitored on-line to the system operator. Different (faster than real-time) stability programs for a number of contingencies can then be run to evaluate risks and margins.

Different kinds of "intelligent" load shedding can be ordered more or less automatically from the SCADA/EMS system in case of energy shortage on the electricity market or other limitations in the power system operation, that can be planned in advance. With access to wide area measurements, such a system can be made adaptive to cope with the actual system conditions, such as load flow pattern and voltage levels.

To clearly distinguish between protection and SCADA/EMS also fits very well with utility and grid company organizations, where the responsibility for protection and SCADA/EMS are usually directed to different departments or divisions within the company.

VII. POSSIBLE DESIGN ARCHITECTURES

Since the requirements for a wide-area protection system can vary from one utility company to another, the architecture for such a system must be designed according to what technologies a utility possesses at the given time. Also, to avoid becoming obsolete, the design must be chosen to fit the technology migration path that the utility in question will take. Three major design approaches are discussed below.

7.1 ENHANCEMENTS TO SCADA/EMS

At one end of the spectrum, enhancements to the existing EMS/SCADA can be made. These enhancements are aimed at two key areas: information availability and information interpretation. Simply put, if the operator has all vital information at his fingertips and good analysis facilities, he can operate the grid in an efficient way. For example, with better analysis tool for voltage instability, the operator can accurately track the power margin across an interface, and thus can confidently push the limit of transfer across an interface.

SCADA/EMS system capability has greatly improved during the past years, due to improved communication facilities and highly extended data handling capability. New transducers such as the PMUs can provide time-synchronized measurements from all over the grid. Based on these measurements, improved state estimators can be derived.

Advanced algorithms and calculation programs that assist the operator can also be included in the SCADA system, such as "faster than real time simulations" to calculate power transfer margins based on contingencies.

The possibilities of extending the SCADA/EMS system with new functions tend to be limited. Therefore it might be relevant to provide new SCADA/EMS functions as "stand alone"

solutions, more or less independent of the ordinary SCADA/EMS system. Such functions could be load shedding, due to lack of generation or due to market price.

7.2 "FLAT ARCHITECTURE" WITH SYSTEM PROTECTION TERMINALS

Protection devices or terminals are traditionally used in protecting equipment (lines, transformers, etc.). Modern protection devices have sufficient computing and communications capabilities that they are capable of performing beyond the traditional functions. When connected together via communications links, these devices can process intelligent algorithms based on data collected locally or shared with other devices.

Powerful, reliable, sensitive and robust, wide area protection systems can be designed based on de-centralized, especially developed interconnected system protection terminals. These terminals are installed in substations, where actions are to be made or measurements are to be taken. Actions are preferable local, i.e. transfer trips should be avoided, to increase security. Relevant power system variable data is transferred through the communication system that ties the terminals together. Different schemes, e.g. against voltage instability and against frequency instability, can be implemented in the same hardware.

Different layers of protection can be used - compare with the different zones of a distance protection. Suppose that a specific area in a 500 kV system should be protected against voltage collapse. A limited number (say 10 to 15) of critical substations (from measurement or action point of view) are identified. Information about voltage levels, reactive power flows, etc., is then exchanged among the critical substations. In a certain substation the local voltage magnitude is used together with, e.g. 7, neighbor substation voltage levels, to form logical decisions. A certain action, such as load shedding, shunt capacitor switch-in or tap-changer blocking, is then made if:
- 6 of the 8 voltages are low (e.g. <480 kV), or
- 4 of the 8 voltages are very low (e.g. <470 kV), or
- the local voltage is extremely low (e.g. <460 kV).

Using the communication system, between the terminals, a very sensitive system can be designed. If the communication is partially or totally lost, actions can still be taken based on local criteria. Different load shedding steps, that take the power system response into account – in order not to over-shed, can easily be designed.

Protection systems against voltage instability can use simple binary signals such as "low voltage" or more advanced indicators such as power transfer margins based on the VIP-algorithm [3], or modal analysis.

The solution with interconnected system protection terminals for future transmission system applications is illustrated in Figure 1 for protection against voltage instability; similar illustration can be done for angular instability.

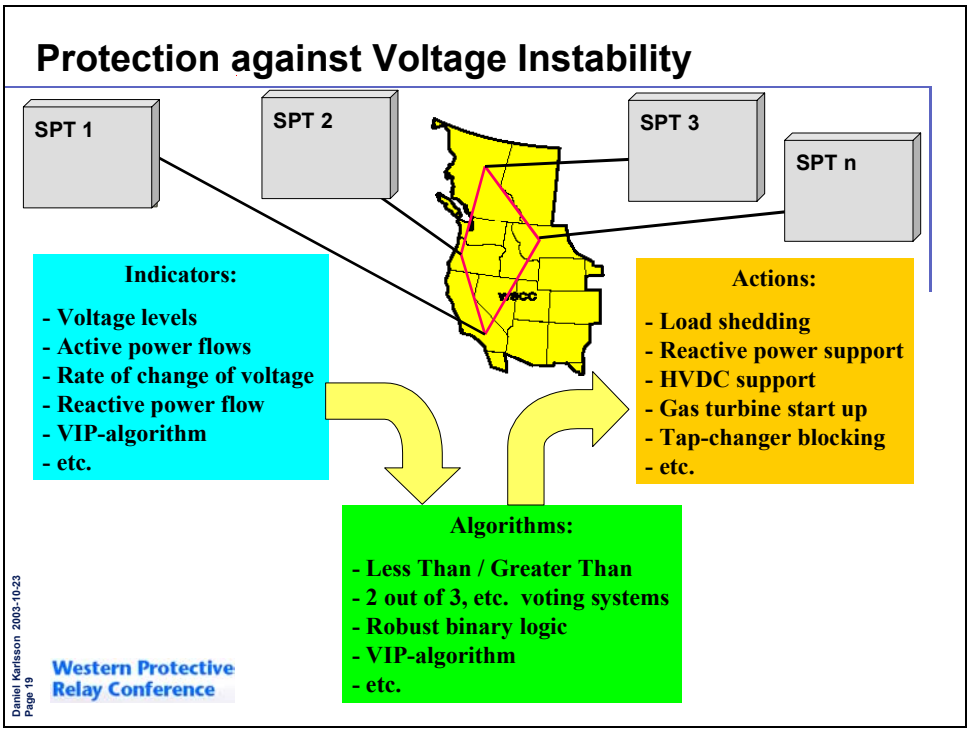

Figure 1: Terminal based wide area protection system against voltage instability

More details about the "flat architecture" are given in [4].

7.3 MULTILAYERED ARCHITECTURE

While the above two designs attempt at extending the "reach" of existing control domains, there is also a possibility to design a comprehensive solution that integrates the two control domains, protection devices and EMS. Such a solution is depicted in Figure 2.

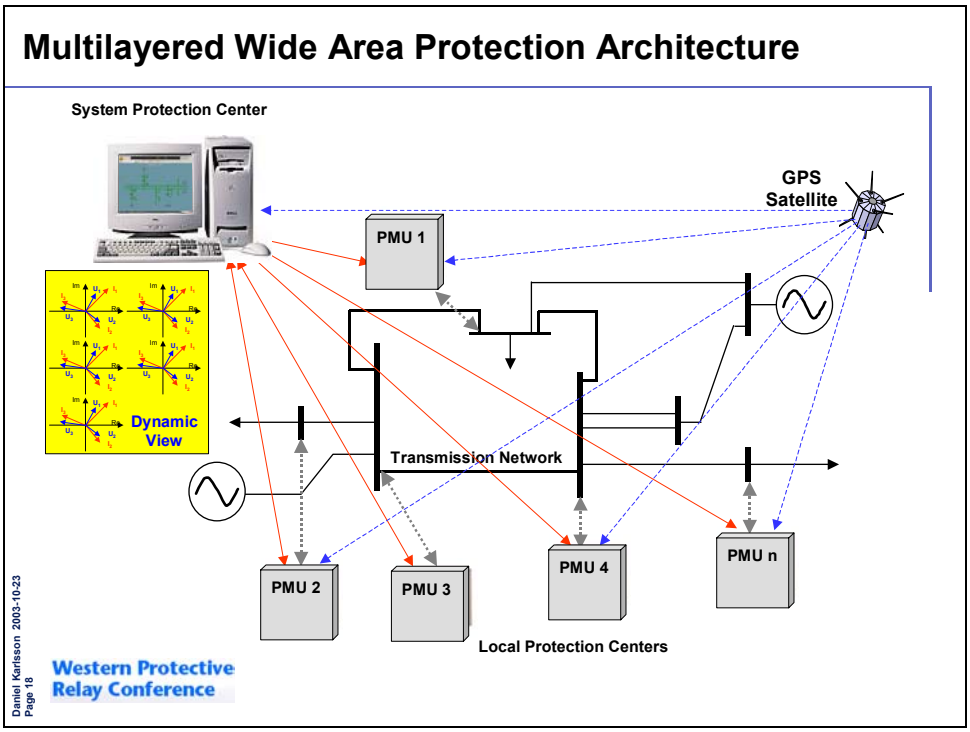

Figure 2: Multilayered wide area protection architecture

There are up to three layers in this architecture. The bottom layer is made up of PMUs, or PMUs with additional protection functionality. The next layer up consists of several Local Protection Centers (LPCs), each of which interfaces directly with a number of PMUs. The top layer, System Protection Center (SPC), acts as the coordinator for the LPCs.

Designing the three-layered architecture can take place in several steps. The first step should aim at achieving the monitoring capability, e.g., a WAMS. Wide Area Measurement Systems (WAMS) is the most common application based on Phasor Measurement Units. These systems are most frequent in North America, but are emerging all around the world. The main purpose is to improve state estimation, post fault analysis, and operator information. In WAMS applications a number of PMUs are connected to a data concentrator, which basically is a mass storage, accessible from the control center, according to Figure 3.

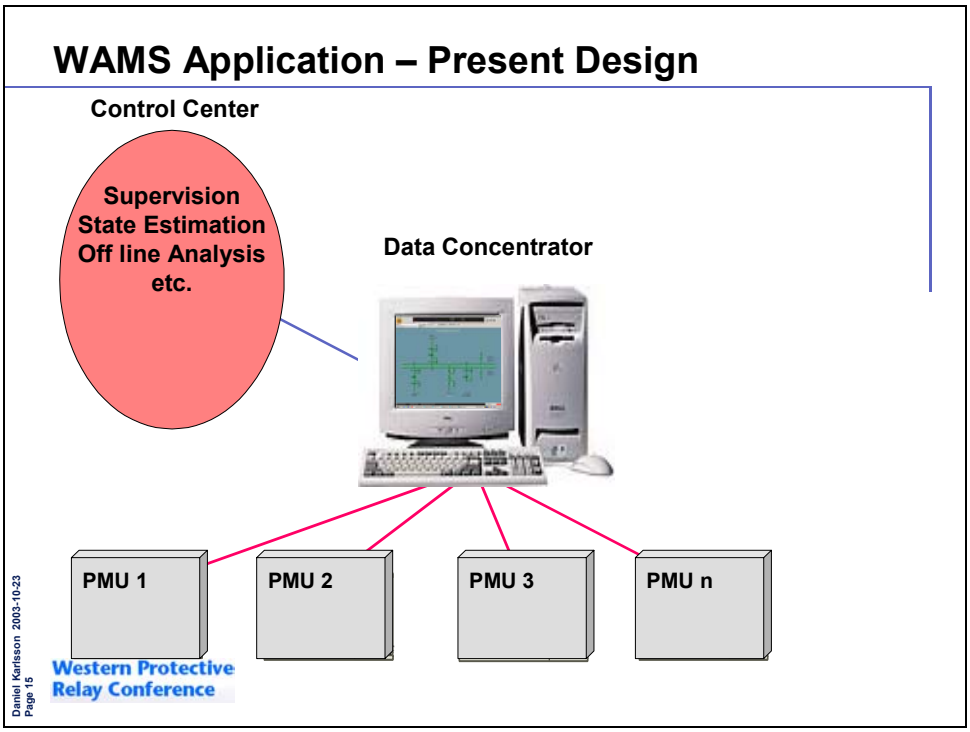

Figure 3: WAMS design

Starting from a WAMS design, a data concentrator can be turned into a hub-based *Local Protection Center* (LPC) by implementing control and protection functions in the data concentrator, Figure 4.

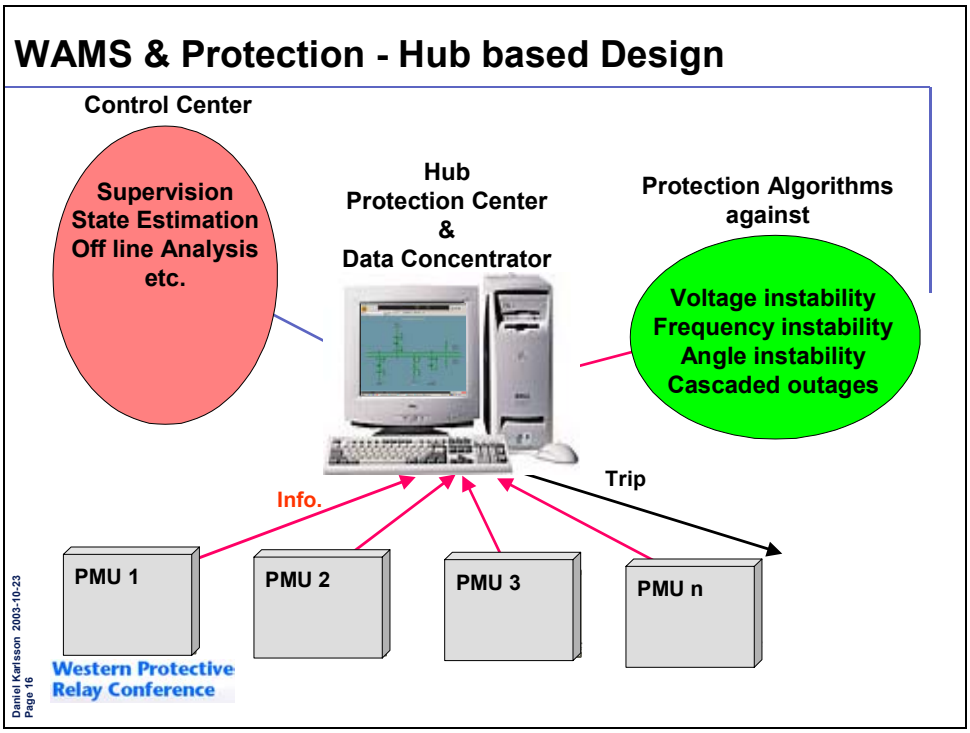

Figure 4: Hub based wide area protection design

A number of such local protection centers can then be integrated into a larger system wide solution with a *System Protection Center* (SPC) at the top, see Figure 2. With this solution the local protection center forms a system protection scheme (SPS), while the interconnected coordinated system forms a defense plan [5, 6].

VIII. DISCUSSION

The meaning of wide area protection, emergency control and power system optimization, may vary dependant on people, utility and part of the world, although the basic phenomena are the same. Therefore standardized and accepted terminology is important.

The solution to counteract the same physical phenomenon might vary extensively for different applications and utility conditions. A certain utility might wish to introduce a complete system to take care of a large number of applications in one shot, while others want to move very slowly with small installations of new technology in parallel with present systems. Some utilities want to do large amount of the studies, design and engineering themselves, while others want to buy complete turn-key systems. It is important for any vendor in this area to supply solutions that fit with different utility organizations and traditions.

The potential, to improve power system performance using smart control instead of high voltage equipment installations, seems to be great.

IX. CONCLUSIONS

This paper has discussed terminology, phenomena and solution implementation strategies for wide area protection. It is concluded that different applications will require different solutions. Therefore system design and equipment must be very flexible both in size and complexity.

The introduction of the Phasor Measurement Unit (PMU) has greatly improved the observability of the power system dynamics. Based on PMUs different kinds of wide area protection, emergency control and optimization systems can be designed.

A great deal of engineering, such as power system studies, configuration and parameter settings, is required since every wide area protection installation is unique. A cost effective solution could be based on standard products and standard system designs.

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BIOGRAPHICAL SKETCHES

Daniel Karlsson received his Ph. D in Electrical Engineering from Chalmers University in Sweden 1992. Between 1985 and April 1999 he worked as an analysis engineer at the Power System Analysis Group within the Operation Department of the Sydkraft utility. From 1994 until he left Sydkraft in 1999 he was appointed Power System Expert and promoted Chief Engineer. His work has been in the protection and power system analysis area and the research has been on voltage stability and collapse phenomena with emphasis on the influence of loads, on-load tap-changers and generator reactive power limitations. His work has comprised theoretical investigations at academic level, as well as extensive field measurements in power systems. Presently Dr. Karlsson has a position as Application Senior Specialist at ABB Automation Technology Products. Through the years he has been active in several Cigré and IEEE working groups. Dr. Karlsson is a member of Cigré and a senior member of IEEE. He has also supervised a number of diploma-workers and Ph. D students at Swedish universities.

Lawrence Broski has received his certificate from Northern Alberta Institute of Technology in Alberta in 1969 in Electrical, and his Registered Engineering Technologist (R.E.T.) in 1986. After graduating he worked with EPCOR where he received his Power Electrician Certificate, and later spent 18 years with Siemens in Canada and Germany. Presently Lawrence has the position of Network Management Sales with ABB Inc. in Edmonton, Alberta Canada.

Sethuraman Ganesan received BE. (Hons.) degree in Electrical and Electronics Engineering from Madras University, India in 1982, with specialization in power systems. He began his career in Tata Consulting Engineers, Bangalore and was responsible for control and protection design of major thermal power stations. In 1985 he joined English Electric as Protection Application Engineer. During this period he was involved in major studies on EHV line fault locators, in collaboration with Indian Institute of Technology, Madras. In 1990 he joined ABB Network Partner, Saudi Arabia as Design Section Head. After 5 years he took over the technical affairs of Deprocon Engg., Bangalore, specializing in protection engineering executions for major generating and EHV system projects in various countries. Since 2001, Ganesan has been working with ABB, Allentown as Senior Protection Application Engineer.

THE VALUE OF MEASUREMENT ACCURACY

The maximum allowable power transfer for a certain transmission line is set with respect to thermal capacity, angular stability or voltage stability. Regardless of how the maximum limit is obtained, the operator must keep a margin to this limit, due to uncertainties in measurement and parameter data. In the following a simple transmission line is studied, see Figure 1.

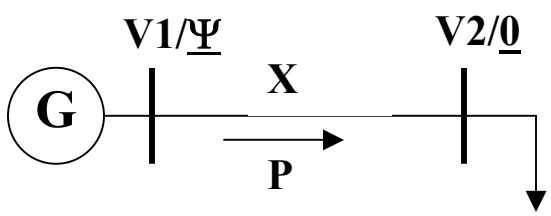

Figure 1. Transmission line for power transmission calculation.

The power transmitted in the system in Figure 1 is calculated, with respect to the measurements, according to:

$$P_{measured}(\Psi) = \frac{V1 * V2}{X} \sin \Psi \tag{1}$$

$P_{measured}$ as a function of the transfer angle Ψ is shown in Figure 2.

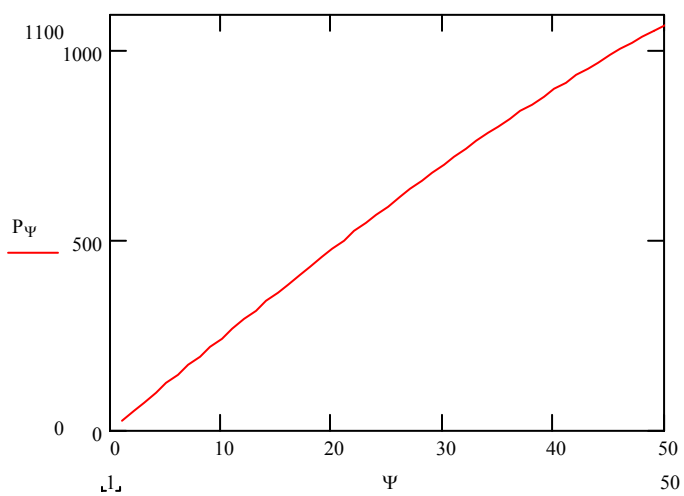

Figure 2. Measured power transfer as a function of the transfer angle.

Let us now assume a measurement accuracy for the different quantities according to Table I. The measured values for V1 and V2, as well as the line reactance X, are also shown in Table I. Case (1) to Case (4) have increasing inaccuracy concerning both magnitudes and phase angles, while

Case (5) has a high accuracy for the magnitudes and a low accuracy for the angle and Case (6) is the other way around.

Table I

Quantity	Measured value	Case (1) Inaccuracy	Case (2) Inaccuracy	Case (3) Inaccuracy	Case (4) Inaccuracy	Case (5) Inaccuracy	Case (6) Inaccuracy
V1	420 kV	0.1%	0.3%	1.0%	3.0%	0.1%	3.0%
V2	400 kV	0.1%	0.3%	1.0%	3.0%	0.1%	3.0%
X	120 Ω	0.1%	0.3%	1.0%	3.0%	0.1%	3.0%
Ψ	1-50 deg	0.1 deg	0.3 deg	0.5 deg	1.0 deg	1.0 deg	0.1 deg

The maximum actual power transfer for the measured values, and different accuracies, can now be calculated. Equation (2) shows how this is done for Case (1).

$$P_{max01}(\Psi) = \frac{V1 \cdot 1.001 * V2 \cdot 1.001}{X \cdot 0.999} \sin(\Psi + 0.1) \tag{2}$$

The difference between the maximum actual power transfer, with respect to the different accuracy levels, and the measured value, can now be calculated, according to Equation (3).

$$P_{diff01}(\Psi) = P_{max01}(\Psi) - P_{measured}(\Psi) \tag{3}$$

Figure 3 shows this difference as a function of the transfer angle, for the inaccuracies shown in Table I.

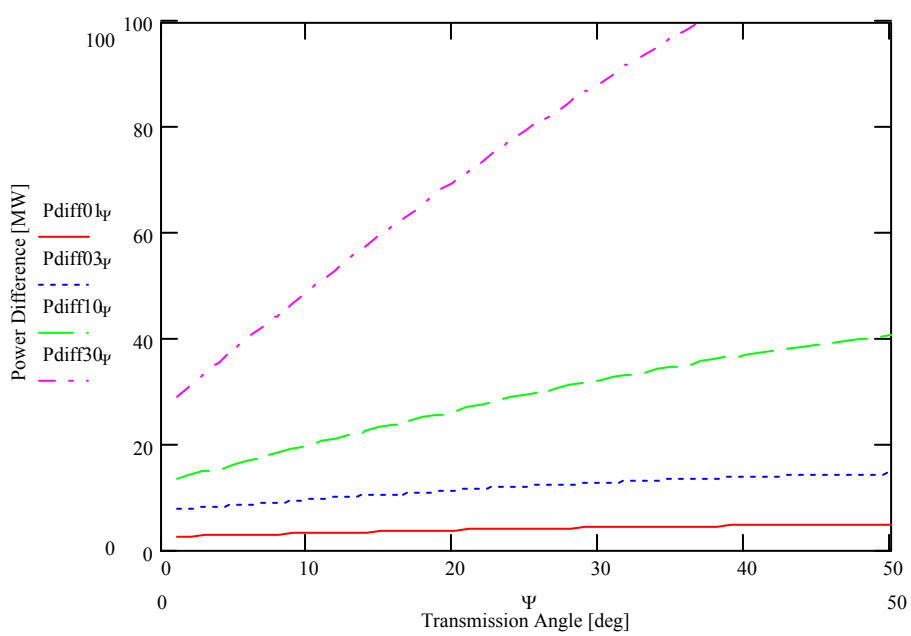

Figure 3. Difference between maximum actual power and measured power.

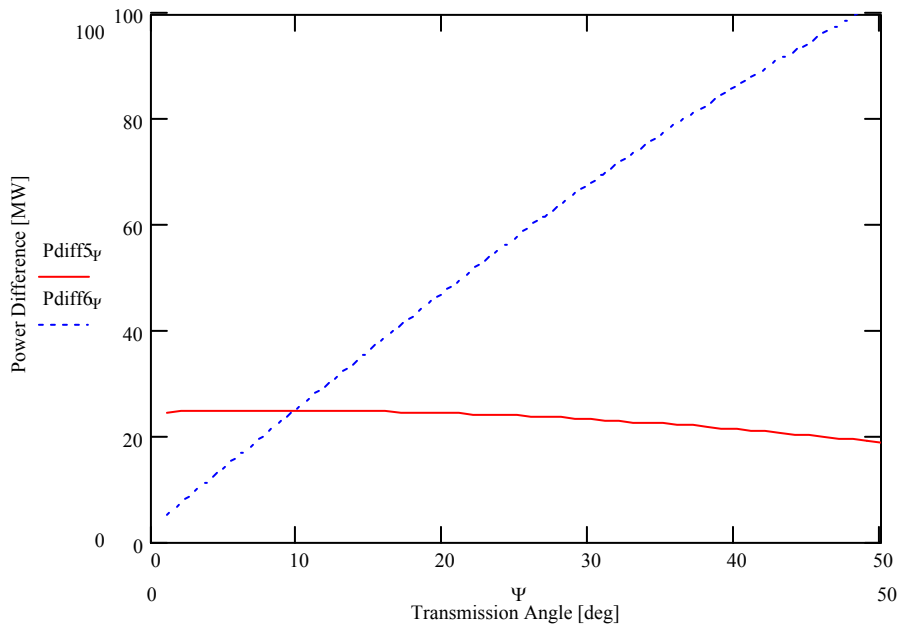

Figure 4. Difference between maximum actual power and measured power, for Case (5&6).

The trend in the diagrams is very clear. However it might be a bit difficult to read out numerical values, therefore a few figures are presented in Table II.

Table II. Difference between actual and measured power [MW]

	Ψ=5°	**Ψ=10°**	**Ψ=15°**	**Ψ=20°**	**Ψ=25°**	**Ψ=30°**	**Ψ=35°**	**Ψ=40°**
Pdiff01	2.7	3.1	3.4	3.7	4.0	4.2	4.4	4.6
Pdiff03	8.3	9.3	10.2	11.1	11.9	12.6	13.2	13.7
Pdiff10	15.5	19.1	22.5	25.7	28.8	31.6	34.2	36.5
Pdiff30	35.8	46.9	57.6	67.9	77.7	86.9	95.4	103.2
Pdiff5	24.7	24.8	24.7	24.4	24.0	23.4	22.5	21.6
Pdiff6	11.8	23.2	34.3	45.2	55.8	65.9	75.6	84.6

Suppose that the transmission line is operated as close as possible to the limit for 100 hours per year and that this limit corresponds to a transfer angle of 30 degrees. Due to the inaccuracy of the measurements, a certain margin to the actual limit must be kept. This margin can be read in Table II (column Ψ=30°) for different measurement accuracies.

Suppose that the value of each extra MWh transferred, on this transmission line during the 100 critical hours, is 20 USD. Cheap remote power has to be replaced with expensive local power, when transfer limits are hit, which gives a value for increased capacity. This will give us a yearly cost for the different accuracies and a tool to calculate the optimal accuracy, which will be when the investment cost of increased accuracy will be equal to the present value of the increased transfer capacity (the present value is often approximated with ten times the annual value).

The yearly cost for limited measurement accuracy, based on the assumptions above, is then shown in Table III.

Table III. Yearly cost for limited measurement accuracy and annual value of improvement.

	Yearly cost [USD]	**Annual value of improvement [USD]**
Pdiff01	8 400	
Improvement: 0.3% -> 0.1%		16 800
Pdiff03	25 200	
Improvement: 1.0% -> 0.3%		38 000
Pdiff10	63 200	
Improvement: 3.0% -> 1.0%		110 600
Pdiff30	173 800	

To get a rough engineering estimate of the investment cost that corresponds to these annual improvements: - Just multiply the annual values by 10.

It has to be remembered that improved accuracy very often is just a matter of serious calibration – to learn to know the non-linearities, etc., of the measurement devices, and to calibrate the readings. It is seldom that the CTs and VTs have to be replaced, to be able to considerably improve the accuracy of the measurements, and thereby the utilization and profitability of the transmission system.

Conclusion

Improved measurement accuracy, primarily by instrument transformer measurement error evaluation – and corresponding calibration tables for the readings – is shown to be a straightforward and very efficient means to improve the utilization and thereby the profitability of transmission systems.