INTEGRATED SUBSTATION AUTOMATION ENABLE NEW STRATEGIES FOR POWER T&D

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ABSTRACT

In view of the envisaged competitive electricity market era, utilities are examining the application of information technology (IT) as an alternative to support corporate business strategies that focus on improving service, power quality and reducing cost of operation and maintenance. Key issues for the improvement of the overall productivity are more and better information concerning the entire system behaviour, service condition of physical assets, e.g. circuit breakers and power transformers, as well as cost efficient operation and maintenance management.

Substation Automation (SA) in comparison with a remote terminal (RTU) concept means decentralisation of computer capacity, which shall be used e.g. for intelligent automatic power restoration procedures after faults and for powerful decentralised processing of service and environment condition related data.

Utility executives, on the other hand, are increasingly examining automation solution alternatives to support corporate business strategies that focus on improving service reliability and reducing cost of operation and maintenance.

In the past, utility engineers often struggled with the fact that too little data was available when they attempted to analyze problems within their power systems. They also did not have enough information to predict or ascertain the level of maintenance needed when it would be required for the major equipment located within their substations. As new and higher levels of digital technologies have made its way into substations in terms of numerical protection devices and control systems, these same engineers are suffering from data overload. They have more data than can be processed and assimilated in the time available. Today the challenge is to automatically convert data to knowledge, which frees manpower to implement corrective or preventive maintenance.

It is suggested that intelligent electronic devices (IED) shall be implemented for protection and control tasks in substations to substitute electro-mechanical or static devices. In a modern SA system these IEDs provide an infrastructure to collect, to process and to transmit data and information, which are utilised for cost effective condition monitoring of circuit breakers, power transformers, instrument transformers etc.

This idea is illustrated by an example for power transformer condition monitoring. The SA system provides a user-friendly overview for the actual transformer condition. This comprises condition-related parameters like: service current, temperatures, and quality of insulation oil, partial discharge measurements and loads.

The integration of the various SA systems in a high performance communication network allows system wide adaptive protection and real time automatic power restoration procedures.

Keywords:
Substation automation, condition monitoring, on-line monitoring of transformers, Internet and browser technology, adaptive protection, wide area protection,

INTRODUCTION

In the increasingly competitive arena there is significant pressure on power providers for greater system reliability and improvement of customer satisfaction, while similar emphasis is placed on cost reduction. These cost reductions focus on reducing operating and maintenance (O&M) expenses, and minimizing investments in new plants and equipment. If plant investments are to be made only for that which is absolutely necessary and the existing system equipment must be pushed to greater limits in order to defer capital investments.

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In the past, utility engineers often struggled with the fact that too little data was available when they attempted to analyze problems within their power systems. They also did not have enough information to predict or ascertain the level of maintenance needed when it would be required for the major equipment located within their substations. As new and higher levels of digital technologies have made its way into substations in terms of numerical protection devices and control systems, these same engineers are suffering from data overload. They have more data than can be processed and assimilated in the time available. Today the challenge is to automatically convert data to knowledge, which frees manpower to implement corrective or preventive maintenance.

WORKING PLANTS HARDER

Various aspects of the utilities needs have been revealed in the Cigré 99 London Symposium on the subject: “Working Plant and Systems harder”. Enhancing the management and performance of plant and power systems is being discussed widely at many international conferences. The overall conclusion perceived is that there are a lot of new technologies available, which will help planners and operators to find new solutions to maximise the use of the power systems and adapt to the fast changing environment.
There are two aspects where Substation Automation (SA) can contribute potential benefits to achieve more power: (Figure 1)

1. Better information, which result in higher productivity
2. Intelligent automation which assures higher availability.

![Figure 1: The potential benefits of Substation Automation](image)

The prerequisite, however, is efficient communication for easy access from remote to primary equipment condition related information and fast inter-station communication. (Figure 2)

![Figure 2: Efficient communication network](image)

**BEETTER INFORMATION**

For once neglecting outages as a result of wrong human operation, there are basically three reasons for power interruptions:

1. The breakdown of a utility asset through normal wear and ageing under working conditions.
2. The breakdown of an asset being effected by an external event (system disturbance), such as a tree falling on an overhead line that led to a permanent abnormal working condition.
3. A temporary system disturbance where either the external influence disappears ("self-healing"), or a protective system isolates the assets from the electric grid, and by means of network redundancy avoids a power outage at all, or leaves a limited area without power. With respect to the condition of assets, however, this temporary disturbance most likely caused accelerated wear.

Condition monitoring mainly addresses the wear and ageing caused by normal or temporarily abnormal working conditions. First, in that they support the evaluation of the actual condition of assets, and second, in that they might explicitly support the prediction of the further evolution of a detected problem, and the probability of breakdown. However, many of today's condition monitoring systems leave the assessment of the future to the human's interpretation based on his conclusions drawn from the current status. Whichever, even if a utility decides, e.g., based on risk management considerations, to let a worn out asset in operation until it breaks, the breakdown will be a planned one, and so will the repair action be. Hence, the power interruption will most likely be rather short and the problems posed by the interruption alleviated as good as possible.

Apart from monitoring the condition of primary equipment and thereby attempting to proactively prevent power interruptions, an elaborate post fault analysis supported by monitoring systems is equally important. It has been observed that a large proportion of major blackouts of electric power systems is caused by protective system failures. These failures are generally hidden and only exposed during the rare occasion of system disturbances. According to utility opinion derived from a questionnaire over 60% of these failures are based on wrong protection settings, protection calibration, or protection maintenance. It is therefore important to capture as much details as possible during a system disturbance and have access to as much protection relevant data as possible during the entire analysis. The conceivable subsequent settings refinement phase is a measure to prevent the same interruption from happening again, or, at least, minimise its impact on the power distribution.

**Data Acquisition**

With computing power making its way into the primary equipment, more and more equipment internal data can be made available to the outside at virtually no cost. Interfaces to acquire such internal data were previously not provided for cost reasons. Data that will be accessible includes, but is not restricted to:

- switching counters,
- thermal information,
- quality of isolation media,
- entire timing curves of switching operations,
- switching currents,
- manufacturing data,
- original value of key performance criteria.
This kind of data can be the source of valuable condition information and exploited for building condition monitoring systems for those assets that exhibit the highest failure rates and/or cause unacceptable power interruption impact. Without doubt the transformers and circuit breakers are the prime candidates for these kinds of monitoring systems.

The second trend within the data acquisition falls into the category of intelligent electronic devices (IED), i.e. secondary equipment like protection terminals. Besides their primary functions, they host more and more additional functionality, which increase their attractiveness compared with dedicated single function units. (Figure 3) Many of these additional functions provide a sound foundation for basic monitoring systems, cost-efficient and perfectly suited for medium and distribution voltage level IEDs for protection or control may comprise:

- Disturbance recorders
- Event recorders
- Statistical value recording (peak current indicators, number of starts/trips, current at tripping, etc.)
- Power quality analysers
- General purpose programming capabilities that allow to write and run customer specific applications on the IEDs.

Integrated Transformer Monitoring

Transformer unavailability has a considerable impact on the operation of electricity generation and installation networks. Monitoring systems available on the market already provide solutions for monitoring the windings and magnetic circuit (e.g. gas dissolved in oil, ultrasound emission, temperatures). Other methods and systems are under development. They all aim to prevent major failures and extend service lifetime of the equipment by triggering preventive maintenance. Furthermore, the use of monitoring data must be coupled with the implementation of diagnostic tools.

SA supports transformer on-line to survey specific condition related data over a long period of time to enable the judgement of the transformer condition with respect to load carrying capability, ageing and development of failures. These data are retrieved from suitable instrument transformers and sensors as shown in figure 4.

Reliability Centred Maintenance

The new approach is to move from the traditional time-based maintenance policy to condition-based reliability centred maintenance (RCM) policy. This calls for differentiation between the following four types of maintenance policy:

- Predictive or condition based maintenance, i.e. to monitor if something is going to fail
- Preventive maintenance, i.e. overhauling items or replacing components at fixed intervals
- Corrective maintenance, i.e. fixing things either when they are found to be failing or when they have failed
- Detective maintenance, i.e. to detect hidden failures by means of special functional checks and diagnostics

The type of maintenance policy to select for specific equipment for transmission and distribution depends on reliability and on economic and customers’ business related availability considerations, which take the consequences of failures into account.

Condition Related Data

The data measured on new transformers are the most important reference data for the later judgement of the actual condition. The most common sensors for on-line condition monitoring are:

- Moisture sensor: The presence of moisture in the transformer oil may be an indication of accelerated ageing of the insulation or an indication of gasket deterioration and inward leakage.
• **Top oil temperature sensor:** Top oil temperature is an indicator of the thermal performance of a transformer.

• **Combustible gas sensors:** Thermal and electrical stresses breakdown the dielectric oil into a variety of gases. The gases are indicative of developing faults in the transformer and early detection will trigger corrective action to prevent costly failures. Such sensors are most sensitive to hydrogen and carbon monoxide.

**Transformer Monitoring via Intranet**

The World Wide Web as an information source and its commercial application has created a mass market where the technology costs are shared by millions of developers and companies throughout the world. The costs for applying these mainstream technologies to other applications like transformer monitoring are relatively low when compared with proprietary solutions for networks, protocols, processors, and software environments.

As an alternative to the integration of on-line monitoring in SA system a stand-alone solution for global access for service and support via the corporate Intranet.

On the server side in the substation condition related raw data are retrieved from the transformer continuously in an asynchronous mode and stored in a database management system (DBMS). The client is installed on a PC in the maintenance department or on a notebook PC of the maintenance engineer. A standard browser e.g. from Netscape serves as human machine interface. The utility homepage contains a button for transformer monitoring, which can only be activated by authorised personnel. If this page is called up, a Java applet is loaded which establishes the connection with the hypertext transfer transmission protocol (HTTP) server on site and the transformer monitoring page is refreshed with actual data from the server database. (Figure 5)

**Retrofit for Critical Transformers**

How critical is the status of an old transformer? Is it really necessary to shut down its operation to find out? Periodic, off-line tests play an important role in evaluating the general condition of transformers. But more and more utilities wish to have better information and are turning to a sophisticated process to collect information while the equipment is still in service. This continuous monitoring of the transformer aims at improved reliability, at early stage detection of problems, and at reduced maintenance cost.

If a problem is detected, which cannot be judged by the utility maintenance staff, the vendor’s support and service centre can be contacted via the Internet

**Information Available via Browsers**

The transformer-monitoring page on a browser shows the following actual service and condition related data. (Figure 6)

- **Service data**
  - Oil temperature
  - Current
  - Voltage
  - Load
  - Tap changer position

- **Service condition data**
  - Fan performance in %
  - Air entry/exit temperatures
  - Oil entry/exit temperatures
  - Oil pump switched on/off

- **Life expectancy related information**
  - Load in % of the rated load
  - Estimated hot-spot temperature
  - Ageing ratio
  - Estimated consumed life time in %
But in the majority of cases, there are neither communication links nor suitable sensors available for transformer monitoring from remote, which makes remote monitoring is not very cost effective. To improve this combination with remote control of the tap changer, load dependent control of the cooling system, and for load adaptive protection enables optimised transformer load control and better utilisation of the transformer. Internet technology, however, provides affordable communication facilities e.g. via telephone networks. A combined transformer monitoring, protection, control and communication package is shown in figure 7.

Figure 7: Retrofit package for critical power transformer

INTEGRATED PROTECTION AND CONTROL

With the introduction of numerical relays, with the realisation of modern substation control systems, and with the development of new communications technologies, direct interaction between protection and control leads to adaptive protection schemes, to intelligent load shedding, and to automatic power restoration procedures. The following examples illustrate how these new functions can be implemented in conjunction with SA concepts as corrective measures to limit the consequences of faults.

Adaptive Protection

The term “adaptive protection” is related to a protection philosophy which permits and seeks to make adjustments in various protection functions automatically in order to make them more attuned to prevailing power system conditions. This means that the function of a protection relay, measuring local process related quantities can be enhanced by additional information about the network.

Distance line protection with transfer bus

The power supply from the public network into an industrial plant is usually highly sensitive against interruptions, as the consequential damages caused may be exorbitant. In order to provide redundancy for the critical line circuit breakers (CB), a transfer bus can be provided and the bus coupler CB can temporarily substitute the faulty line CB (Figure 8). This means, however, that the bus coupler needs to be equipped not only with busbar current differential protection $P_C$ but also with distance protection $P_L$, which can be adapted to the impedances of the various lines.

The corrective measures, which are automatically initiated in case faulty line circuit breakers (CB) to restore the power, would be:
1. Isolation of the line CB
2. Initiation of all by-pass connections
3. Activation of the correct distance protection

Figure 8: Distance Protection with Transfer Bus

Compensation of mutual impedance

The next critical areas of failures are the redundant power lines feeding into an industrial plant, which often run in parallel over long distances. The automatic switching of the load from one line to the other as a corrective measure in case of one line being faulty, has to take into account that mutual impedance exists between the parallel lines. This impedance can cause measuring failures, resulting in unnecessary trips initiated by the associated distance relays during earth faults. In order to avoid this, the distance protection needs to be automatically adapted to the topology of the parallel lines and to the actual service conditions (e.g., parallel, disconnected, earthed or unearthed, both lines connected to different busbars at one side, etc.). Apart from this, also the power carrying capability of one of the lines may have to be increased by corresponding adaptation of the line protection.

The scheme for the corresponding exchange of information between the line bay control units and the line bay protection units as well within the substation itself as between associated substations is shown in figure 9. It is crucial that this communication is of very high quality with regard deterministic and real time speed behaviour. It is therefore recommended to
establish a communication link, which is dedicated for this adaptive protection task.

![Figure 9: Topology based adaptation of line distance protection](image)

**DYNAMIC LOAD SHEDDING**

Load shedding is a typical corrective measure to assure uninterrupted power supply to vital areas of an industrial plant, if there is an under-frequency condition due to lack of power.

The conventional load shedding approach is static, as it initiates tripping of pre-selected circuit breakers when a certain level of under-frequency is reached, regardless of the actual load conditions. The reason is that the actual load behind each individual circuit breaker is not taken into account.

Microprocessor based load shedding schemes, however, are in the position of considering the actual loads and to dynamically select only those feeders to be opened, which are needed to regain the frequency stability.

![Figure 10: Dynamic load shedding scheme](image)

Load shedding functions can be allocated to a protection or a control device associated with the various bays of an SA system.

The load shedding function block (LSFB) of the dynamic load shedding scheme continuously monitors the load of each feeder. (Figure 10) It obtains the actual measured current and voltage values either directly hardwired from dedicated CT’s and a busbar VT or via communication links from the CT’s and VT’s, which are incorporated in the numerical protection/control devices.

The LSFB compares the reference power $P_{ref}$ with the individual feeder load measurements $P_1...P_n$. To each feeder a priority index $P_i$ is assigned for load shedding. The LSFB selects from the power inputs $P_1...P_n$ the sum of the power which is larger than $P_{ref}$ thus minimising the difference between the selected and reference power. If the pre-determined load shedding criteria (LSC) in terms of under-frequency ($< f$) or frequency change ($> \frac{df}{dt}$) is fulfilled, a predefined percentage $X \%$ of total load $P_{tot}$ is shed by opening selected feeders. The selection of the feeders to be opened also takes the predefined priority index $P_i$ into account.

If the network frequency continues to drop or remains stable on an under-frequency level, the shed of the next load class is initiated, i.e. shedding of a second predefined percentage $X\%$ of the total load $P_{tot}$ (Figure 11). Otherwise, if the network frequency starts to increase within a definable time delay, the next load class will not be enabled and the load shedding scheme is reset as soon as the network frequency has recovered. If the network frequency has recovered, the integrated network restoration function will be started automatically.

![Figure 11: Dynamic Load Shedding](image)

**Benefits**

In contrast to the conventional way of load shedding, stabilisation of the frequency can often be reached in the first shedding step. In addition, only the necessary load is tripped resulting in a minimum impact for the plant supply.
Network Restoration
Another important feature of the microprocessor based load shedding is selective network restoration, which is comprised of two steps:

1. **Generation increase**: If the load balance is reached the network frequency will get stable on a lower level. To recover the network frequency, activating the generation reserve will increase power generation. The load frequency controller leads the network frequency back to the nominal value.

2. **Network restoration**: The load shedding program has stored the tripped feeders. After the restoration of the frequency the feeders are reconnected one by one. Each reconnected feeder causes a minor load unbalance, which leads to a certain frequency reduction immediately restored by the load frequency controller. This frequency supervision avoids network collapse during the restoration phase.

**DISTRIBUTED SA VERSUS RTU**

The remote terminal unit (RTU) concept as shown in figure 12 comprises the following features:

**Centralised RTU**
- Communication to network control centre
- Bay oriented remote control
- Bay oriented numerical protection
- Retrieval of data from numerical protection
- Communication between RTU and IEDs (Master/slave mode)
- Support of IEC 870-05-103 protocol

![Figure 12: Centralised RTU Concept](image1)

As an integrated alternative, the distributed SA concept as shown in figure 13 comprises the following features:

**Distributed integrated SA**
- Communication to network control centre
- Bay oriented remote control
- Integrated bay oriented numerical protection
- Retrieval of data from numerical protection
- Communication between RTU and IEDs (Peer-to-peer mode)
- Support of fast interaction between IEDs
- Automated intelligent power restoration
- Retrieval of condition related data
- Maintenance server with direct access

![Figure 13: Distributed integrated SA concept](image2)

The comparison between the range of functionality makes it obvious that the only the distributed integrated SA concepts offers the benefits for more power by supporting the issue for better information, which leads to higher productivity, as well as the automation aspect to achieve higher availability.

**WIDE AREA PROTECTION**

A new technology has been developed for the detection of incipient voltage instabilities. Such systems comprise a number of Phasor Measurement Units (PMU) and a central evaluation unit. The PMUs are located at strategic points throughout the power system. (Figure 13) They contain an algorithm that calculates the stability of the various power line transfer conditions based on local measurements of voltage and current phasors.

![Figure 13: Distributed integrated SA concept](image3)
Response to Incipient Voltage Instability

In case of incipient voltage instability detection, two types of instructions are issued:

1. Alerting the system operator by indication of the remaining safety margin $S$ and by providing on-line guidance to counteract this situation. In addition, corresponding information is produced as input for the energy management system (EMS).

2. Automatic control actions are initiated if the safety margin $S$ reaches a pre-set critical level to avoid voltage instabilities to occur, e.g.
   - To compensate the lack of reactive power by FACTS (Flexible AC Transmission Systems)
   - To block the OLTCs (On-lin Tap Changer Controller) in order to avoid over compensation.
   - To maximise the reactive power output from synchronous machines, to compensate the lack of reactive power.
   - To shed load as last defence measure

The block diagram below shows the interactions between the various applications.

Decision Support Systems

During disturbed condition data from disturbance recorder, information on network configuration, protection relay signal data and operational procedures all need to be considered when arriving at the appropriate decision for corrective action. This can be problematic due to data volumes and the limitations to the amount of information and real-time performance, which can be managed from SCADA and handled by an operator. The advantages of an automated system located in the substations, which accelerates the automation process, are obvious. The corresponding system structure below shows the allocations of functions and the communication links.

CONCLUSION

The SA infrastructure comprising numerical protection and control devices allows a new maintenance approach for T&D equipment and provides cost effective solutions for

- On-line monitoring of primary and secondary substation equipment
- Diagnostics to determine the need for maintenance
- Reliability-centred maintenance and condition based asset management

The benefits are reduction of operation and maintenance costs as well as improved service quality and overall power system availability

The integration of protection and control is a way to minimise installation and maintenance complexity by reducing the number of IEDs in a substation. Thorough research studies have indicated that the integration of protection and control functions will even increase the system reliability. The improvement arises largely from the reduced amount of hardware, wiring and interfaces between equipment that are enabled by integrated solutions.

This conclusion has a very important impact on substation automation and power system monitoring concepts as it makes a combined protection, control and monitoring concept not only economical but also superior in reliability in comparison with a centralised RTU concepts and separate IEDs control and protection.

A further advantage of this approach is that automated responses on incipient system faults are enabled. Large area outages caused by voltage instabilities and frequency declines can be counteracted by means of wide area protection schemes, adaptive protection for transmission lines, intelligent load shedding and automated defence plans power system restoration.

System Restoration

The two objectives to be achieved during any major disturbance are

1. To preserve the integrity of the transmission grid by shedding load and/or generation as required
2. To restore supply to all consumers in the shortest possible time

With an effective islanding system in place considerable advantage can be obtained from well-designed auto-restoration schemes. Integrated numerical control and protection devices in a substation automation system enable to design intelligent automated restoration schemes.