Intelligent Transformer Substations in Modern Medium Voltage Networks as Part of "Smart Grid"

Helmut Späck, Bernd Schüpferling, Jürgen Riemenschneider, Meinolf Schelte
Siemens AG, Germany, Sector Energy, Power Distribution, Medium Voltage

***Abstract*-- Higher utilization of the power systems, variable load flows due to decentralized power generation from renewable energy sources and a growing need for information of the regulating authorities place higher demands on fault detection and acquisition of system operating data. Furthermore, remote indication and remote control can considerably reduce supply interruption times as well as system breakdown costs, and provide rapid adjustment to varying load conditions.**

Therefore, the requirements for the intelligence of transformer substations will increase in the future. But where are the limits of useful and cost-efficient utilization? They are somewhere between a merely passive substation and the complete automation.

With the gas-insulated medium-voltage switchgear type 8DJH, Siemens offers the basis for application in an intelligent transformer substation. It is optionally equipped with motorised operating mechanism; short-circuit indicators and voltage detecting systems, as well as a variety of other sensors. Plug-connected to a Remote Terminal Unit (RTU) in a separated wall-mounting cabinet, the switchgear fulfills all preconditions for integration in an intelligent network infrastructure.

This article provides an overview on different intelligence levels, possible kinds of communication to the telecontrol system as well as necessary components and requirements of future intelligent transformer substations.

***Index Terms*—**
3-Points-Automation
Fault Localization
Gas-Insulated Medium-Voltage Switchgear
Intelligent Transformer Substations
Load Flow Control
Monitoring
Remote Control
Remote Terminal Unit
Secondary Distribution Level
Smart Grid

I. INTRODUCTION

Modern life needs electrical energy: at any place, any time requiring high quality. Increasing demand for electricity – especially in developing countries – and the concerns about global warming are the motors to push renewable energy sources in many countries. In addition, high efforts are made to reduce power losses wherever possible. Renewables like wind power or photovoltaics are sponsored in many countries by law, like the law for renewable energies EEG ("Erneuerbare-Energien-Gesetz" [1], [2]) in Germany. The increase of renewables changes the structure of the networks. On the other hand, the number and time of outages are the basis for the "grid fees", its upper limits, or penalties in some countries.

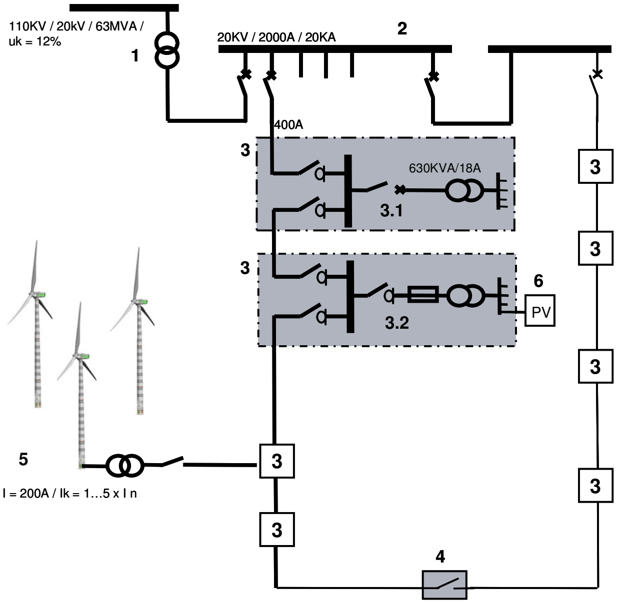
In the past there was only one principle: power generation follows load. So, there was only one direction of energy flow: from the power plant to the consumer.
Today, a lot has changed. Renewable energies are generated in a decentralized way according to suitable locations. Energy is usually fed into the network at the medium-voltage or low-voltage level; in some cases, even directly into the high-voltage network. An essential feature of renewables like wind power and photovoltaics is the stochastic availability. This has a great influence on network the control into existing distribution system.
Besides there are other effects such as:
- Changed direction of energy flow
- Changed cable load
- Higher short-circuit currents
- More difficulties with power quality
- Additional demand for balancing energy
- Changed requirements on the protection concept

In the future, power consumption will follow generation rather than vice versa. Prime examples are electric cars that can be charged or operated at night drawing on cheap wind power. This means a change towards a paradigm shift: leaving uni-directional energy and communication flows behind for bi-directional power flows [3]. Therefore, new intelligent and flexible solutions have to be identified and developed.

One module of the future smart grid is the intelligent transformer substation enabling automatic and fast fault clearance, thus contributing to active load management in secondary distribution systems.

II. SECONDARY DISTRIBUTION SYSTEM DESIGN WITH DECENTRALIZED POWER SUPPLY

Figure 1 shows an overview diagram for a typical medium-voltage system for the secondary distribution level in Central Europe, including decentralized power supply on the medium-voltage and low-voltage side.



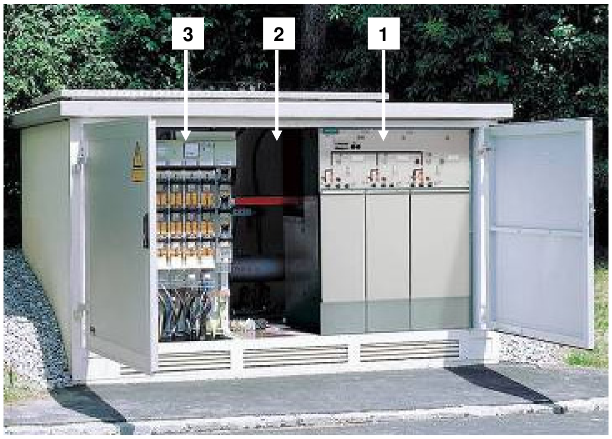
Legend:
1 Power transformer
2 Circuit-breaker switchgear of the primary distribution level
3 Secondary transformer substation with Ring Main Unit (RMU)
3.1 RMU with circuit-breaker
3.2 RMU with switch-fuse combination
4 Secondary transformer substation with RMU, with open sectionalizer
5 Decentralized power supply, wind power
6 Decentralized power supply, photovoltaics

Figure 1: Secondary Distribution System Design with Decentralized Power Supply

The key data for the circuit-breaker switchgear of the primary distribution level and for the distribution system basically result from the data of the power transformer. Today, circuit-breaker switchgear of the primary distribution level are fully automated and integrated in the substation automation system.

At the secondary medium-voltage level, cable systems with compact HV/LV-transformer substations are mostly used, as shown in Figure 2. Presently, secondary transformer substations are not included in the "substation automation system" in most of the cases, and can therefore not be monitored or telecontrolled. The secondary distribution system is mostly operated as an open ring, i.e. with an open sectionalizer in one transformer substation.

Apart from the RMU with switch-fuse combination (IEC 62271-105) or circuit-breaker, the transformer substations are equipped with the distribution transformer and the low-voltage switchgear with fuse blocks or low-voltage circuit-breakers.



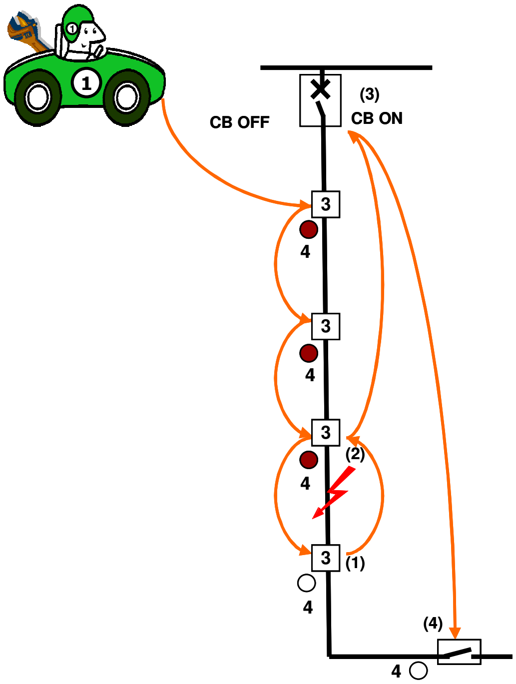
Legend:
1 Ring-Main Unit
2 Distribution transformer
3 LV equipment

Figure 2: Typical HV/LV-Transformer Substation

Statistics from power supply companies referring to supply interruptions at the end customer show that e.g. in Germany about 80% of the interruptions are caused by failures in the medium-voltage system. The System Average Interruption Duration Index (SAIDI) describes the total time of all interruptions for customers, divided by the number of customers. Typical values for a German municipal utility are 10 minutes of annual outage per customer. In other regions of the world the outage times reaches from hours to days. The utilities' customers require maximum availability of the electrical power supply.

Manual Fault Localization - Current Status

As secondary transformer substations are usually not equipped with communication links to the network control centers, monitoring of faults as well as remote control are not possible. This can cause long supply interruptions, thus restricting the reliability and security of supply to a large extent. Fault detection is also impaired by the long distances to the secondary transformer substations, which leads to even longer outage times.



Legend:

3 Transformer Substation
4 Short Circuit / Earth Fault Indicator
● tripped
○ not tripped

Figure 3: Manual Fault Detection

The procedure for fault clearance according to figure 3 is normally done in the following way:

- When a fault occurs in the distribution system, the upstream circuit-breaker (CB) in the transformer substation trips (CB OFF), so that all substations up to the open sectionalizer are not supplied.
- An intensive and time consuming fault detection process starts by driving to the individual secondary transformer substations and reading the short-circuit or earth-fault indicators. The ring is opened at the substation where the short-circuit or earth-fault indicator has not responded (1). After returning to the previous substation, the ring is also opened there (2), so that the fault is isolated and can be cleared later.
- Now the tripped upstream circuit-breaker can be closed again ((3) – CB ON).
- Finally the sectionalizer will be closed (4).

After this procedure the complete ring is supplied again, and the faulty section in the ring can be repaired.

The described procedure for fault clearance requires a lot of time and a large number of personnel. A highly qualified service expert has to drive to many substations to identify the fault prior to supplying all customers with power again. This produces financial losses for utilities by not supplying energy to households and companies.
Therefore, there is great need for intelligent and automated solutions.

III. INTELLIGENT TRANSFORMER SUBSTATIONS

The topic “Intelligent Transformer Substations” is intensively discussed on many technical conferences and expert circles at the moment.

There are three different levels of an intelligent transformer substation:

- Level 1: Monitoring
  → higher availability by faster fault localisation
- Level 2: Monitoring + remote control
  → minimizes breakdown times by fast fault clearance
- Level 3: Monitoring + remote control + load flow control
  → minimizes losses
  → manages decentralized power supplies

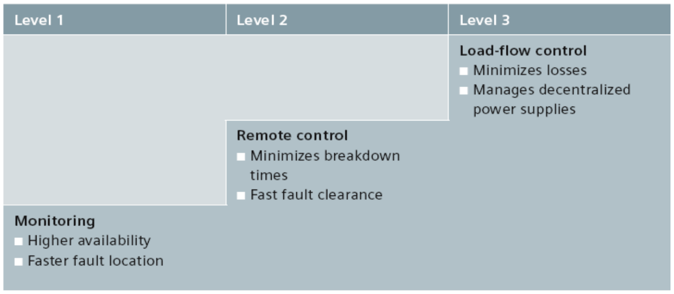


Figure 4: The Three Different Levels of an Intelligent Transformer Substation [4]

Intelligent Transformer Substations – RTU – Communications – Network Control Center

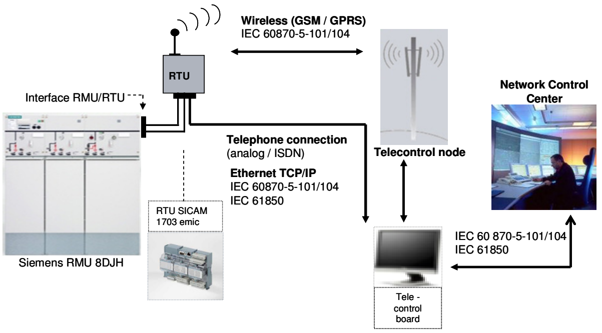


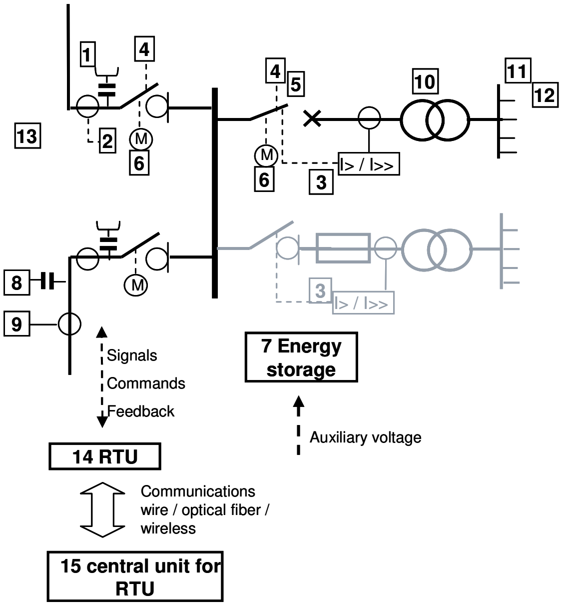
Figure 5: Substations – RTU – Communications - Control Level

Figure 5 shows the basic structure of an intelligent transformer substation with communication link via the Remote Terminal Unit (RTU) to the telecontrol node or the network control center.

Ring-Main Unit (RMU) / Transformer Substation with Sensors and Actors

RMU with sensors and actors are the basis of an intelligent transformer substation. Depending on the objective, different components are used for monitoring and control according to figure 6:

- The voltage detecting system (1) shows whether the outgoing feeders are live or not
- Short-circuit/earth-fault indicators (2) signal a short-circuit or earth-fault in accordance with the adjusted operating threshold.
  Depending on the network structure and the direction of the energy flow, it may be necessary to use devices with detection of direction which require an adequate voltage information
- Overcurrent-time protection systems (3) with auxiliary contacts are used for transformer protection
- Auxiliary switches (4) are available, e.g. for position indications, interlocks, releases, gas pressure
- Stored-energy operating mechanisms with solenoids (5) and motor operating mechanisms (6) are available for remote closing and opening
- Voltage and current sensors (8/9) transmit the voltage and current signal for the purpose of load flow control. The signals are derived from conventional voltage or current transformers or from modern sensors.



Legend:

1	Voltage detecting system
2	Short-circuit/earth-fault indicator with operating threshold
3	Overcurrent-time protection for distribution transformer
4	Auxiliary switches
5	Stored-energy mechanisms / solenoids
6	Motor operating mechanisms
7	UPS (Uninterruptable Power Supply) energy store
8/9	Voltage/current monitoring
10	Transformer monitoring
11/12	Monitoring of low-voltage distribution + possibly customer connection
13	Monitoring of substation
14	RTU (Remote Terminal Unit)
15	Central unit / control level

Figure 6: Components for Monitoring and Control

The new gas-insulated medium-voltage switchgear type 8DJH [5] provides all functions for applications in intelligent substations and fulfils all preconditions for integration in an intelligent network infrastructure.
Later retrofitting of components for remote control can be performed easily and very quickly.

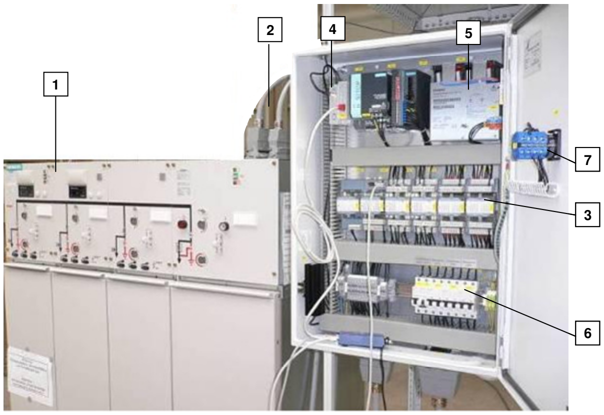
Additional sensors/information according to figure 6 are available in the transformer substation for:

- Transformer monitoring (10) with sensors for temperature, pressure and oil level
- Monitoring of the low-voltage distribution in the transformer substation (11)
- If required, data from the customer's side can also be integrated (12)
- Monitoring of the substation itself like door lock or temperature (13), e.g. for object supervision

Remote Terminal Unit (RTU)

There are two main tasks of the remote terminal unit (14): on the one hand providing the signals and measured values or information from the transformer substation for communication to the telecontrol node or network control center. On the other hand the RTU transfers the necessary commands to the actors and monitors the execution thereof.

Figure 7 shows a real installation of the 8DJH RMU with a complete RTU box, delivered to a German utility.



Legend:
1 RMU 8DJH
2 Plug connection interface
3 RTU SICAM TM 1703
4 Modem for wireless communication
5 UPS with power supply units + battery
6 Mini Circuit Breaker (m.c.b.)
7 Local remote switch

Figure 7: Siemens RMU 8DJH with RTU for Remote Control

A plug connection interface between RMU and RTU box is required by many customers for several reasons:

- Easy installation of the RTU box in substations
- Use of the same RTU box for new and old substations
- Easy exchange in case of new sophisticated technology or in case of failure

The RTU box is designed and manufactured by the switchgear manufacturer or by the utilities.
The main components of the RTU box shown in figure 7 are normally:

- Basic RTU module with extension modules if necessary, e.g. Siemens SICAM TM 1703 emic
- Communication module
- Energy store (battery or capacitor)
- LV equipment like m.c.b. and local-remote switch

Modern RTUs can be modularly extended. They feature several communication interfaces, and are designed and tested for the rough environmental conditions of a transformer substation.

Energy Store

The components of an intelligent transformer substation require a reliable auxiliary voltage supply. If the auxiliary voltage fails, an energy store supplies the components for time periods reaching from few minutes to two hours.
The size of the energy store mainly results from the power demand to maintain the RTU function and the communication modules. In contrast to this, the energy consumption for motor-operated CLOSING and OPENING of an 8DJH disconnector operating mechanism is very low.

Conventional batteries and capacitor stores with double layer capacitors (ultracaps) or a combination thereof are mainly used as energy stores. Special batteries are also available for extreme environmental conditions.

Communication – Control Level

As shown in Figure 5, communication from the RTU / transformer substation can take place in different ways, via wire (e.g. Ethernet TCP/IP), optical fibre, or wireless (e.g. GSM/GPRS) to the network control center. There the information is processed, and control commands are communicated back to the RTU's, if required. In the future, communication via WiMAX or BBPL (Broad Band Power Line) will become more important.

The communication protocols follow the standards of IEC 60870 - 5 - 101 and – 104. With a WiMAX or BBPL communication infrastructure, communication standards as per IEC 61850 could also be used in the future.
The utilization of these protocols ensure interoperability between devices from different manufacturers.

The following points, which are also important for selecting the communication medium, are discussed in expert circles:

- Availability and reliability of the communication channels
  Redundancy required?
- Management of the data flood
- Data security/encryption
  Protection against hacker attacks
- Costs for investment and running operating costs
- Risk by "ageing of technology" that is used due to fast IT evolution

Other Topics in Discussion Concerning Load Flow Control

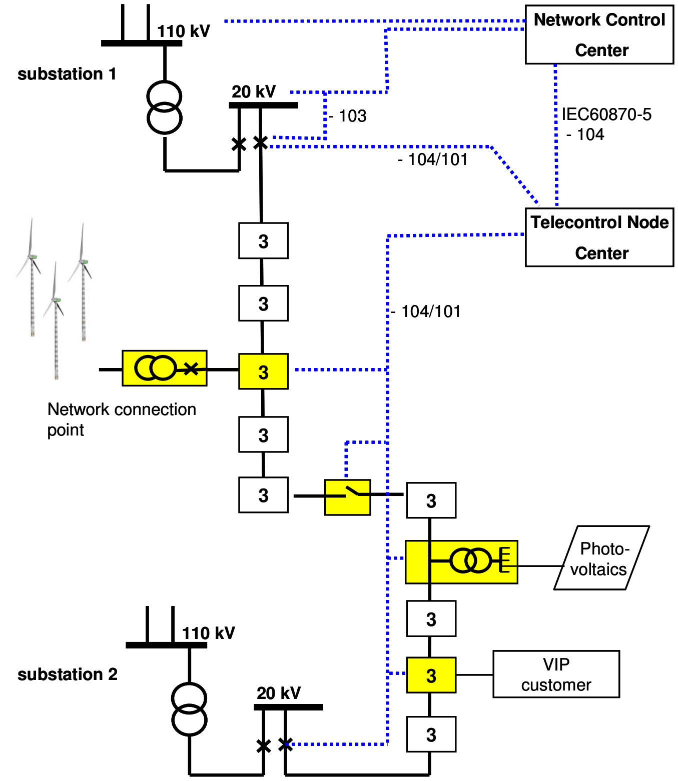
Reducing network losses, increasing the capacity for energy transport and increasing the network stability are the goals.
Topics in discussion are:

- Compensation of reactive power and harmonics by the invertors of wind power and photovoltaics.
- Which balancing mechanisms are optimal to minimize losses and stabilize the network?
- Are distribution transformers with automatically controlled tap changers required?
- How can distribution transformers be controlled during peak loads and monitored in the overload range?
- Can these measures contribute to postpone/avoid network extensions?

Siemens has long years of experience in network planning, and is thus able to elaborate an optimized solution in accordance with the different requirements under the existing network conditions in cooperation with the customer.

Intelligent 3-Points-Automation

Cost-benefit estimations urge many power supply companies to compromise and not to automate the complete distribution system, but only to operate selected important transformer substations in a 3-points-automation, as exemplarily shown in figure 8. Automation can also be retrofitted and adapted to switchgear from different manufacturers.



Legend:

3 Transformer Substation
☐ not-automated
🟨 automated

Figure 8: 3-Points-Automation Principle

Fault clearance with 3-Points-Automation

The procedure for fault clearance in a system with 3-point-automation is as following:

- A fault in the distribution system trips the upstream circuit-breaker in the transformer substation; thus, all substations up to the open sectionalizer are not supplied.
- Fault location by signaling the short-circuit indicators of the automated substations to the network control center.
- In the automated transformer substation, the switching device of the ring is opened by the network control center in the direction of the fault.
- Depending on the location of the fault, either the tripped circuit-breaker in the transformer substation or the switching device at the open isolating point can be closed, so that all important customers are supplied again within a very short time.
- Finally the service expert has to drive straight to the ring section with the fault. There he performs the necessary switching operations to ensure that all customers are supplied again and the faulty section in the ring can be repaired.

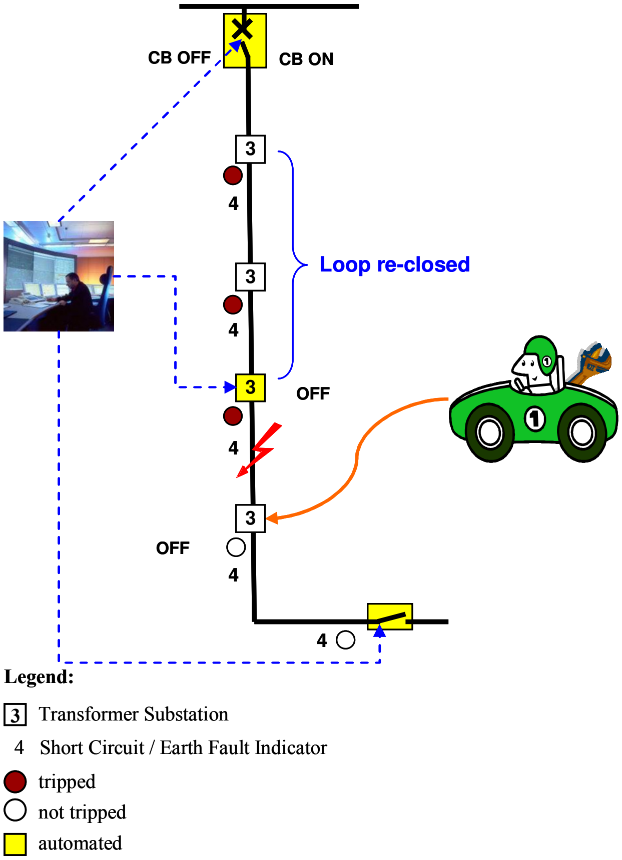


Figure 9: 3-Points-Automation Fault-clearance Procedure

The advantages of this system already utilized by some power supply companies in Germany are much shorter outage times, as well as less expenses for technical personnel for fault detection. Very important customers can be resupplied within minutes.

IV. CONCLUSION

Increasing demand for reliable electricity and achieving the climate protection targets lead to promote the renewable energies with points of infeed in the medium-voltage and low-voltage systems. Maintaining the necessary power quality and network stability requires an active distribution system with intelligent transformer substations.

Possible measures reach from pure monitoring via remote control up to targeted load flow control, and are different in the companies or countries. There is everything from “zero level” up to complete remote control of the transformer substations.

Incentive systems to minimize outage times, and necessary measures to secure the voltage quality are the drivers. Presently, the fault detection with monitoring and remote control with shifting of the open isolating point with the sectionalizer are still in the foreground. Utilization of inverters from the wind power and photovoltaic systems to ensure and improve the power quality will increase in the future. Moreover, distribution transformers with tap changers will be used at critical points in the secondary distribution system. In addition to this there are possibilities for minimization of losses in the grid and monitored utilization of the operational equipment even in the overload range.

The advantages resulting from remote control and active load management are:
- Faster fault localization
- Shorter interruption times
- Measuring/signaling of operational data
- Reduced network losses
- Possibility of compensation of reactive power / harmonics
- Monitored transformer operation during overload
- Higher transmission power; thus: postponement of network extensions
- Remote object supervision

For the upcoming tasks, Siemens has a consistent concept and the suitable equipment:
- Medium-voltage switchgear 8DJH with the necessary sensors and actors [5]
- RTU telecontrol system with SICAM TM 1703 [6]
- Communication via IEC 60870-5-101/104 or IEC 61850 protocols; conventionally via wire, radio or in future via WiMAX or BBDL
- Telecontrol node / substation automation systems SICAM PAS [7] or SINAUT Power CC
- Application/consulting competence through our “network planning” department [8]

The answer to the question “Intelligent transformer substation: a need or luxury?” is: Intelligent substations and an intelligent distribution network are a must in order to meet the requirements of the future.
The objective of Siemens is to continue developing intelligent solutions for the management of secondary distribution systems, thus contributing to reliable and efficient power supply.

A. Figures and Tables

B. Abbreviations and Acronyms

BBPL = Broad Band Power Line
CB = Circuit Breaker
EEG = Erneuerbare Energien Gesetz = Law on renewable Energy
HV = High Voltage
LV = Low voltage
m.c.b. = Mini Circuit Breaker
RMU = Ring-Main Unit
RTU = Remote Terminal Unit
SAIDI = Systems Average Interruption Duration Index
UPS = Uninterruptable Power Supply
WiMAX = Worldwide Interoperability for Microwave Access

V. ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of Katharina Feuerecker and Ansgar Müller for their work on the layout, revision and finishing of this document.

VI. REFERENCES

[1] EEG – Erneuerbare-Energien-Gesetz; Website des Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit http://www.erneuerbare-energien.de/inhalt/ June 14th, 2010

[2] Internationaler ETG (Energietechnische Gesellschaft)-Kongress 2009; Fachtagung 1: Intelligente Netze ETG-Fachbericht 118; VDE Verlag, Berlin

[3] Smart Grid, Siemens Internet Website: http://www.energy.siemens.com/hq/en/energy-topics/smart-grid/, June 10th, 2010

[4] Brochure: Intelligent transformer substations in smart grids Siemens AG, Power Distribution Division, Order No. E50001-D710-A370-X-4A00, 2010

[5] Detailled product information on Siemens 8DJH: http://www.energy.siemens.com/hq/en/power-distribution/medium-voltage-switchgear/gis-secondary/8djh.htm, July 7th, 2010

[6] Detailed product information on Siemens SICAM 1703 http://www.energy.siemens.com/hq/en/automation/power-transmission-distribution/substation-automation/sicam-1703/tm-1703-emic.htm, July 7th, 2010

[7] Detailed product information on Siemens SICAM PAS: http://www.energy.siemens.com/hq/en/automation/power-transmission-distribution/substation-automation/sicam-pas/sicam-pas.htm

[8] Detailed product information on Siemens Network Planning: http://www.energy.siemens.com/hq/en/services/power-transmission-distribution/power-technologies-international/network-consulting/strategic-network-planning.htm

VII. BIOGRAPHIES

Helmut Späck was born in Germany in 1950 and received his diploma at the Berlin Technical University in Physical Engineering Science.

He joined Siemens in 1976 as design engineer and was responsible in different positions in the area of R&D and strategic purchasing especially in the Medium Voltage Factory for gas-insulated switchgear in Frankfurt.

Bernd Schüpferling was born in Germany in 1971. He made an apprenticeship in electrical engineering at the Siemens Technical Academy which he finished as Associate Engineer in 1994.

After successful completion of his apprenticeship, he worked in the field of medium-voltage switchgear including some time in Portugal. Currently he is a Product Lifecycle Manager for 8DJH switchgear and its role within Smart Grid.

Jürgen Riemenschneider was born in Germany in 1951. He studied electrical engineering and graduated at the electrical department of the University of Osnabrück, Germany, as an electrical engineer.

Since 1979 he has worked at Siemens AG, medium voltage switchgear factory in Frankfurt, in different positions throughout the manufacturing of switchgear, and for the last years as a Project Engineer, responsible for the design of low voltage control and protection equipment of gas-insulated medium-voltage switchgear.

Meinolf Schelte was born in Germany in 1956. He studied electrical engineering and graduated at the electrical department of Soest at the University of Paderborn, Germany, as an electrical engineer.

Since 1981 he has worked at Siemens AG in different positions throughout the company, and for the last years in sales of medium-voltage switchgear. Currently he is responsible for sales of gas-insulated medium-voltage switchgear in six European regions.