ADVANCED TAPCHANGER CONTROL TO COUNTERACT POWER SYSTEM VOLTAGE INSTABILITY

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SUMMARY

The main purpose of the automatic tapchanger control (ATCC) for power transformers with load tapchanger (LTC) is to keep the voltage on low voltage (LV) side of the transformer within a preset deadband. Originally ATCC was designed in this way in order to compensate for the voltage drop across power transformer impedance caused by flow of the load current. Therefore an ATCC shall react and change tap position in accordance with LV side load variations. However, the ATCC will as well react on abnormal voltage variations on the high voltage (HV) side of the power transformer. Sometimes such ATCC behavior is not desirable because it just further increases the total load on the HV system (i.e. transmission system). Especially, such behavior shall be prevented during critical operation states of the transmission system, such as a slow power system voltage collapse.

The major power system blackouts throughout the world in 2003 have clearly illustrated the need for different modes of voltage control, since the requirements during normal operation conditions and abnormal conditions, sliding towards voltage instability, are very different. In this paper the focus will be on possibilities to improve traditional load tapchanger control in order to perform properly also during stressed situation in the power system.

Most of the current commercially available automatic tapchanger controllers, just measure the LV side voltage of the power transformer in order to control tap position. Such a principle has a major drawback that typically speeds up a power system voltage collapse. However, some modern intelligent electronic devices (IEDs) used for such automatic control do have the capability to measure the power system voltage on both sides of the power transformer.

A scheme with such built-in feature can offer excellent performance of ATCC scheme during large voltage variations on the transformer HV side. In the same time it can as well be used to improve time coordination of the LTCs connected in series and to minimize the overall number of LTC operations in the whole power system.

INTRODUCTION

When the load in a power network is increased the voltage will decrease and vice-versa. To maintain the network voltage at a constant level, power transformers are usually equipped with a load tapchanger. The tapchanger alters the power transformer turns ratio in a number of predefined steps and in that way changes the secondary side voltage. Each step usually represents a change in LV side no-load voltage of approximately 0.5-1.7%. Standard tapchangers offer between ± 7 to ± 17 steps (i.e. 15 to 35 positions).

The ATCC is designed to regulate a power transformer with a motor driven load tapchanger. Typically such control scheme regulates voltage at the secondary side of the power transformer. The control method is based on a step-by-step principle which means that a control pulse, one at a time, will be issued to the tapchanger mechanism to move it up or down by one position. The pulse is generated by the ATCC whenever the measured voltage, for a given time, deviates from the set reference value by more than the preset deadband (i.e. degree of insensitivity). Time delay is used to avoid unnecessary operation during short voltage deviations from the pre-set value.

AUTOMATIC LTC CONTROL PRINCIPLES FOR SINGLE TRANSFORMER

A typical ATCC measures the busbar voltage (U_{BB}) at the power transformer LV side, and if no other additional features are enabled (i.e. line drop compensation) this voltage is used for voltage regulation. The voltage control algorithm then compares U_{BB} with the set target voltage (Uset) and decides which action should be taken.

Because this control method is based on a step-by-step principle, a deadband ΔU (i.e. degree of insensitivity) is introduced in order to avoid unnecessary switching around the target voltage. The deadband is typically symmetrical around Uset as shown in Figure 1. Deadband should be set to a value close to the power transformer's LTC voltage step. Typical setting is 75% of the LTC step.

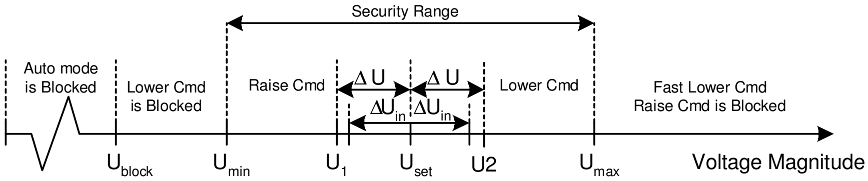

Figure 1: Typical ATCC Voltage Scale for Automatic LTC Control

During normal operating conditions the busbar voltage U_{BB}, stays within the deadband. In that case no actions will be taken by the ATCC. However, if U_{BB} becomes smaller than U1 or greater than U2 (see Figure 1), an appropriate lower or raise timer will start. The timer will run as long as the measured voltage stays outside the inner deadband. If this condition persists for longer than a preset time, the appropriate lower or raise command will be issued. If necessary, the procedure will be repeated until the busbar voltage is again within the inner deadband.

The main purpose of the time delay is to prevent unnecessary LTC operations due to temporary voltage fluctuations. The time delay may also be used for LTC co-ordination in radial distribution networks in order to decrease the number of unnecessary LTC operations. This can be achieved by setting a longer time delay for ATCCs located closer to the end consumer and shorter time delays for ATCCs located at higher voltage levels.

CONTROL PRINCIPLES FOR PARALLEL TRANSFORMERS

Automatic load tapchanger control of parallel transformers can be made according to three different methods:

1) Reverse reactance method
2) Master–follower method
3) Circulating current method

Unlike the first method, the last two methods require exchange of signals and measured values between the transformers, or between the transformers and a central control unit. However, the drawback with the first method is that the voltage control will be affected by changes in the load power factor. The master–follower method is generally limited to applications with similar transformers, whilst the circulating current method, which is typically available in new numerical ATCCs, also handles, in an elegant way, the more generic case with unequal transformers in parallel operation.

Two main objectives of voltage control of parallel transformers with the circulating current method are:

1) Regulate the LV side busbar voltage to the preset target value
2) Minimize the circulating current, in order to achieve optimal sharing of the reactive load between parallel operating transformers

The first objective is the same as for the voltage control of a single transformer while the second objective tries to bring the circulating current, which appears due to unequal LV side no load voltages in each transformer, into an acceptable value. Figure 2 shows an example with two transformers connected in parallel. If transformer T1 has higher no load voltage (i.e. UT1) it will drive a circulating current which adds to the load current in T1 and subtracts from the load current in T2. It can be shown that the magnitude of the circulating current in this case can be approximately calculated with the following formula:

$$\left|I_{cc\_T1}\right| = \left|I_{cc\_T2}\right| = \left|\frac{U_{T1} - U_{T2}}{Z_{T1} + Z_{T2}}\right|$$

Because transformer impedances are dominantly inductive it is possible to use only the transformer reactance in the above formula. At the same time this means that transformer T1 circulating current lags the busbar voltage U_{BB} for almost 90º, whilst transformer T2 circulating current leads the busbar voltage by almost 90º. This also means that the circulating current is mainly reactive in nature, and it only represents reactive power that circulates between two transformers connected in parallel. Therefore by minimizing the circulating current flow through the transformers, the total reactive power flow through the parallel-connected transformer group is optimized as well. At the same time, at this optimum state the apparent power flow is distributed among the transformers in the group in direct proportion to their rated power.

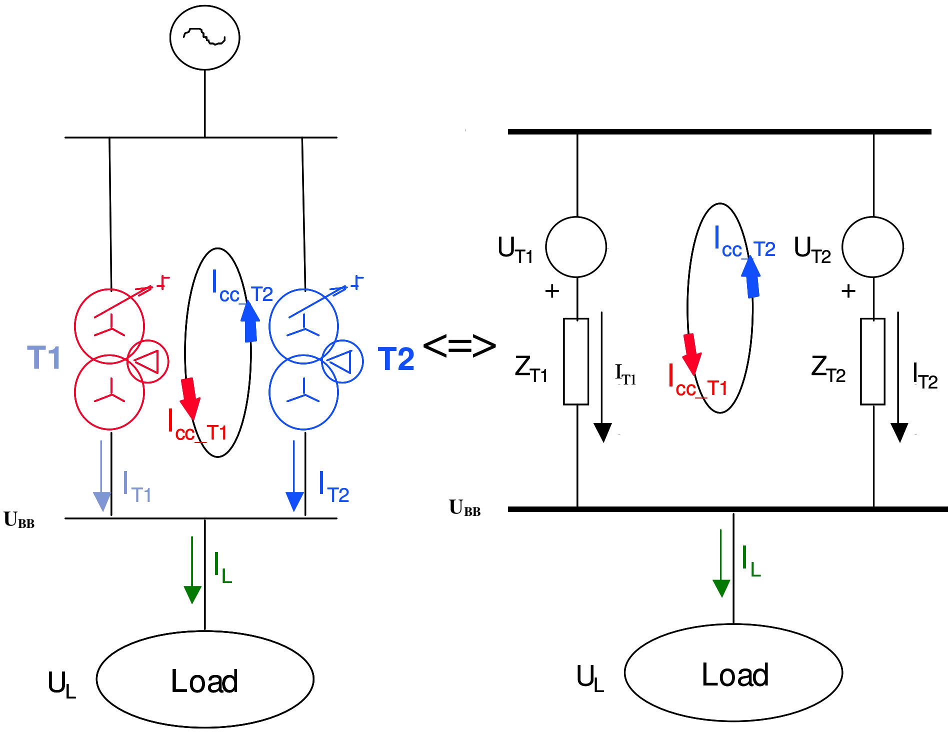

Figure 2: Equivalent scheme for two parallel transformers in accordance with minimizing circulating current method

Therefore an ATCC, regardless of whether it is used for single or parallel transformer control, always reacts and changes tap position in accordance with LV side load variations. However, the ATCC will as well react on abnormal voltage variations on the high voltage (HV) side of the power transformer. Sometimes such ATCC behavior is not desirable because it just further increases the total load on the HV system (i.e. transmission system). Especially, such behavior shall be prevented during critical operation states of the transmission system such as a slow power system voltage collapse [1], [2] & [3].

REALIZATION POSSIBILITIES FOR TRANSFORMER PARALLELING

The transformer paralleling can be realized in two different ways:

1) ATCC functionality for each transformer is integrated in the transformer protection IED. Integration of several protection and control functions in a single IED is common praxis for some electric utilities across the world since 1998. Thus, all power transformer protection functions like 87T, 87N, 50/51, 50N/51N, 49 as well as LTC control function 90 are integrated into a single device. All required information for either master-follower of circulating current operating modes are communicated between the participating IEDs using the IEC 61850-8-1 protocol. Thus, exchange of all analog and binary data for ATCC operation is made by using IEC 61850 GOOSE messages [9]. Up to eight transformers can be controlled in parallel for such installation. Note that for such set-up paralleled transformers can even be located in different substations if corporate LAN is available. Example of such installation is shown in Figure 3.
2) ATCC functionality for all transformers in the station is integrated in a single IED which is only used for parallel LTC control. Such solution eliminates any need for external communication but it requires CT and VT wiring from all LTC transformers to be brought to a common location. Note that it is possible to achieve hot standby functionality by using “backup IED” with identical control facilities as shown in Figure 4 which is taken from one existing installation.

Which of the two solutions is used depends on the end user preference.

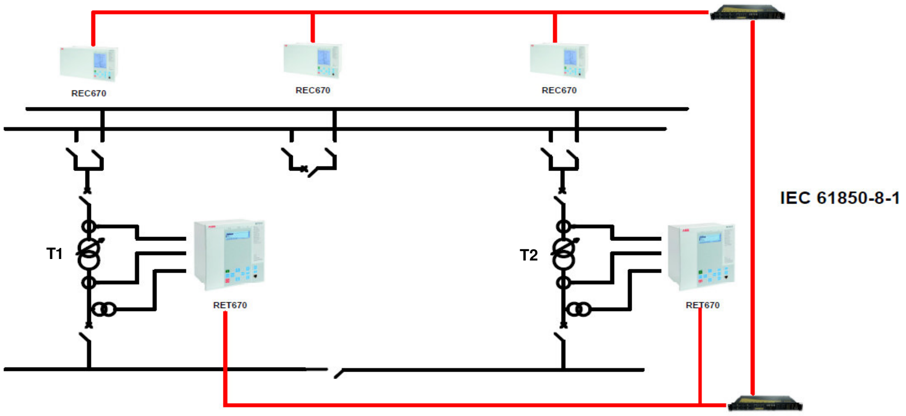

Figure 3: Integration of ATCC functionality in the transformer protection IEDs

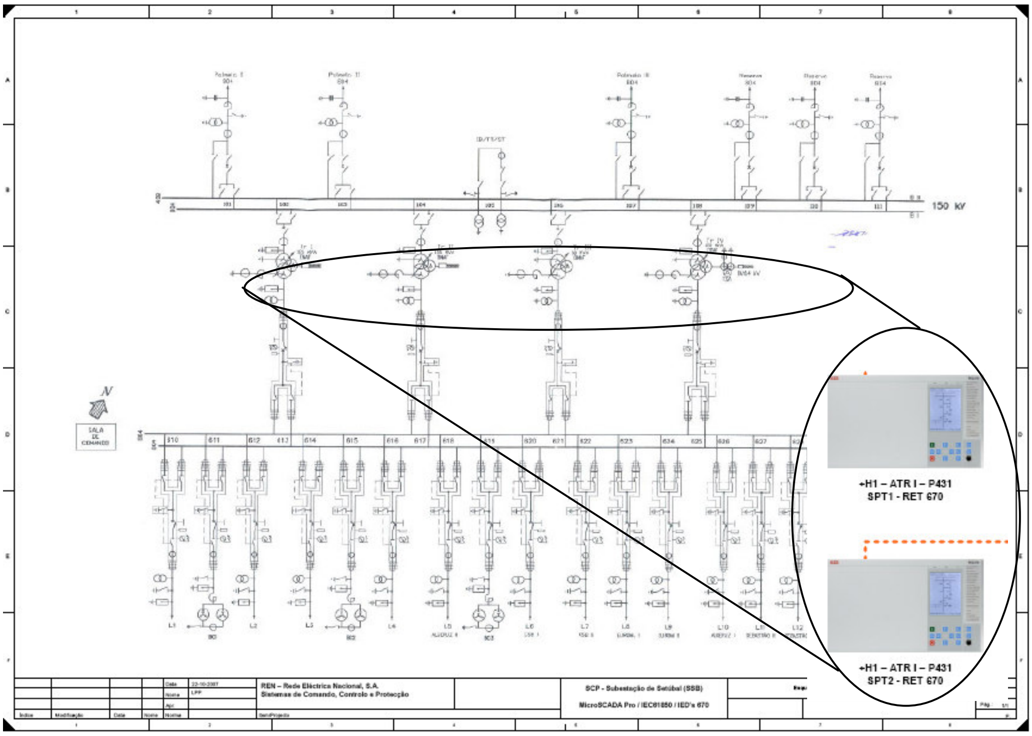

Figure 4: ATCC functionality for four transformers integrated into single control IED with a hot standby functionality

KNOWN WEAKNESSES OF TRADITIONAL ATCCS

The list of well-known weaknesses of traditional ATCC is given here:

1) Radial active power flow from HV to LV side is assumed for correct operation. Special measures shall be taken in case of active power reversal.
2) Time coordination of cascading ATCCs can be quite difficult task in order to minimize number of overall LTC operation in a power system and still keep acceptable time delay for ATCC installed closest to the loads [4]&[5]
3) Quite inefficient way to control voltage for power transformers which interconnect two quite strong networks (i.e. between two transmission networks like 400/220kV autotransformers)
4) Increase of voltage on LV power transformer side worsens the situation on the other side (reactive power flow increases from HV to LV side of power transformer)
5) LV side load recovery by ATCC action during slow voltage collapse in power system [1]

However in this paper only the problems mentioned in points 2) and 5) above will be addressed.

LESSONS LEARNED FROM SWEDISH BLACKOUT IN SEPTEMBER 2003

The major disturbances throughout the world in 2003 have clearly illustrated the need for different modes of voltage control, since the requirements during normal operation conditions and abnormal conditions, sliding towards instability, are very different. In the following, focus will be on possibilities to improve tapchanger control in order to perform properly also for disturbed conditions. Figure 5 shows HV side voltage and tap position for a power transformer connected between 400kV transmission system and 130kV sub transmission system, in the affected area, at the end of the Swedish blackout in 2003 [6]. The used ATCC is designed only to keep the voltage at the low voltage side of the power transformer within certain limits, around the set point.

When the transmission side voltage decreases, the tap position is increased by ATCC in order to fulfill its task. As a consequence, the tap position increases nine steps within last 80 seconds of the blackout, keeping up the sub transmission voltage – and thereby the load – drawing more active and reactive power from the already weakened transmission system. Similar ATCC behaviors have as well been reported during other blackouts, which happened in last 20-30 years all around the world.

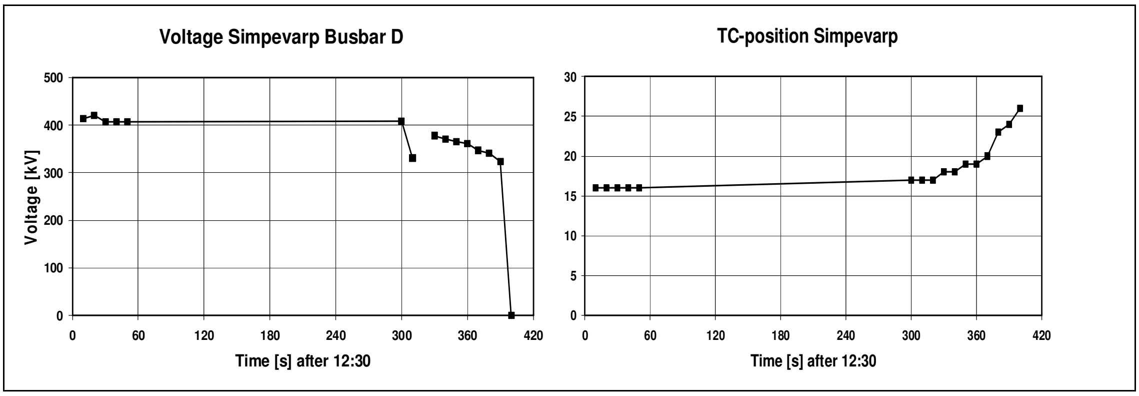

Figure 5: Recorded transformer HV side voltage and tap position at the end of the Swedish blackout in September 2003

ADVANCED ATCC OPERATING PRINCIPLES

The main purpose of the automatic tapchanger control for power transformers with load tapchanger is to keep the voltage on low voltage side of power transformer within a preset deadband. Originally ATCC was designed to compensate for the voltage drop across power transformer impedance caused by flow of the load current. Therefore an ATCC shall react and change tap position in accordance with LV side load variations. However, the ATCC will as well react on abnormal voltage variations on the high voltage side of the power transformer. Often such reaction is not desirable because it just further increases total load on the HV system (i.e. transmission system). Especially, such behavior should be prevented during critical operation states of the transmission system, such as a slow power system voltage decrease, as shown in Figure 5. Typically modern commercially available tapchanger controllers just measure the LV side voltage of the power transformer in order to make decisions about suitable tap position. Such a principle has a major drawback that typically speeds up a power system voltage collapse [1]. However, some modern intelligent electronic devices (IEDs) [7] used for such automatic control do have the capability to measure power system voltage on both sides of the power transformer, as shown in Figure 6. Additionally the total reactive and/or active power flow through the power transformer can be measured as well.

Note that voltage transformers are typically available on the HV side of the power transformer due to other reasons e.g. HV distance protection. By using a number of over- and under-voltage stages it is then possible to monitor HV side voltage magnitude and consequently influence the operation of the ATCC or other equipment in the substation. For the best scheme security it is desirable to measure all three phase-to-earth voltages from the HV side, in order to take necessary action only when all three voltages are above or below the pre-set level. At the same time prolonged presence of negative or zero sequence voltage will indicate possible problems with HV VT. Therefore, operation of the ATCC can be easily influenced, in the secure way, by the level of measured voltage on the HV side of the power transformer. The following are some typical actions, which then can be automatically taken by such ATCC scheme:

1) Temporary ATCC block (e.g. for 20 s).
2) HV shunt capacitor (reactor) switching.
3) ATCC voltage set point change (typically reduction).
4) Complete ATCC block.
5) Undervoltage load shedding.

Temporary block of local ATCC for smaller voltage deviation on power transformer HV side can also be used to drastically improve the cascading ATCC time coordination in a power system. Small voltage variations on the HV power transformer side can be only corrected by the appropriate action of the upstream ATCC. Therefore the local (i.e. downstream) ATCC can be temporary block in order to give additional time to the upstream ATCC in order to react and correct HV voltage magnitude. By doing so the operating time of all cascading ATCCs can be set to the exact the same value. Such scheme will as well guarantee faster voltage control at distribution loads than what is achieved today with traditional time coordination approach. At the same time the temporary blocking will guarantee operation of downstream ATCC in case of failure of the upstream ATCC. With such approach overall number of LTC operations in complete power system can be minimized. This will represent cost benefit for the power utility regarding required LTC maintenance.

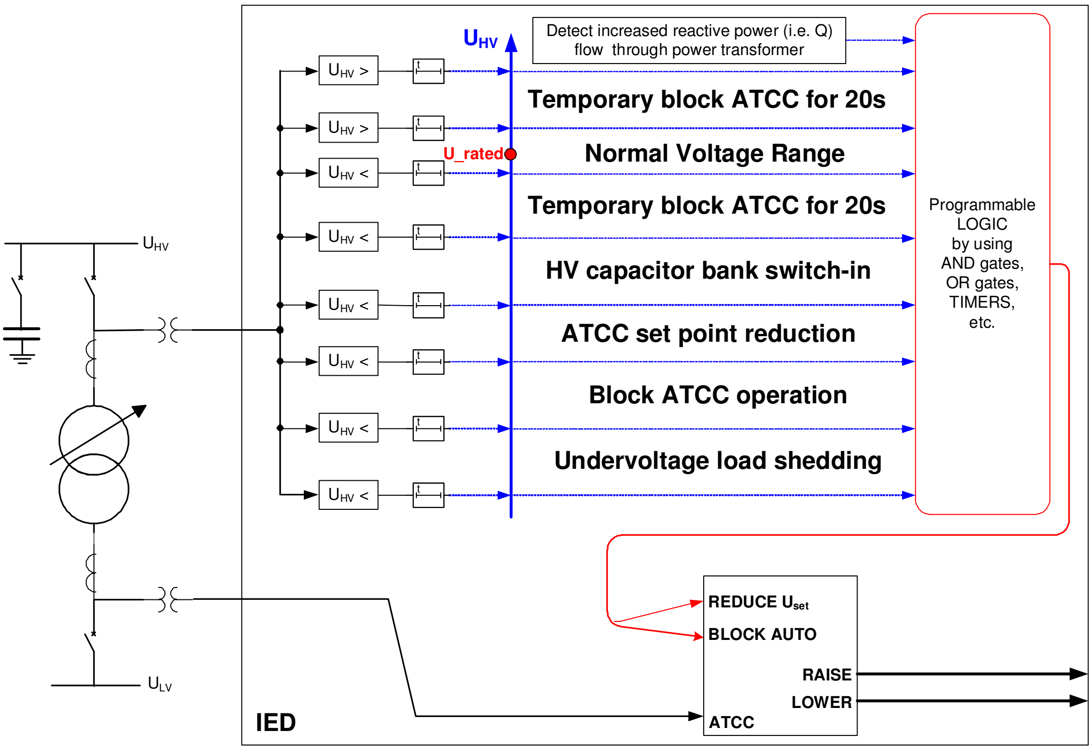

Figure 6: Principles of an improved automatic tapchanger control scheme.

When HV voltage drops to even lower value this might indicate the possible problems in the HV transmission system e.g. slow voltage collapse phenomenon. Therefore the proposed scheme can take certain precautions locally as for example:

1) HV shunt capacitor switching and shunt reactor disconnection, in order to try to increase voltage on the HV side of the power transformer.
2) ATCC voltage set point reduction, in order to keep low voltage profile on sub transmission system and therefore cause reduction of total active and reactive power demand from HV transmission system.
3) Complete ATCC block in order to prevent any tapchanger automatic operation. This will inhibit undesirable ATCC operations during stressed condition on the HV side of the power transformer.
4) Finally undervoltage load shedding of pre-selected outgoing feeders on power transformer LV side can be performed in order to try to prevent complete power system blackout.

Which exact actions shall be taken depends on the particular power system characteristics, location of power transformer within the power system and type of load connected on power transformer LV side. Therefore a complete power system study must be performed in order to determine the optimum scheme setup. However, with help of graphical configuration tools, modern numerical IEDs [7] can be tailor made to fulfill strict requirements of any power system operator and characteristics of the individual power system.

Note that in Figure 6 scheme for a single transformer is shown. However exactly the same scheme can be engineered for parallel operating transformers.

CONCLUSIONS

This paper focuses on new possibility for advanced automatic LTC control strategy for power transformers. The main improvement from the traditionally used schemes is that the newly proposed scheme takes in consideration the voltage magnitude on the HV side of the power transformer. By doing that the overall coordination of series connected power transformers with LTC can be much improved and in the same time performance of such ATCC scheme will be much better during critical situations in HV power system e.g. slow voltage collapse phenomenon.

ACKNOWLEDGEMENT

The paper is based on work performed within the CRISP: distributed intelligence in **CR**itical **I**nfrastructures for **S**ustainable **P**ower, financially supported by the European Commission, contract nr. ENK5-CT-2002-00673: CRISP, which is gratefully acknowledged [8].

REFERENCES:

[1] Taylor, C.W.: "Power System Voltage Stability", McGraw-Hill, 1993.

[2] Taylor, C.W.: "Concepts of Undervoltage Load Shedding for Voltage Stability", IEEE Transactions on Power Delivery, vol. 7, no. 2, pp. 480-488, April 1992.

[3] Ingelsson, Karlsson, Lindström, Runvik and Sjödin: “Special Protection Scheme against Voltage Collapse in the South Part of the Swedish Grid”, 1996 CIGRE Conference in Paris

[4] Mats Larsson: “Coordinated Voltage Control in Electrical Power Systems”, Dissertation, Lund University, Sweden, December 2000.

[5] Daniel Karlsson: “Voltage Stability Simulations Using Detailed Models Based on Field Measurements”, PhD Dissertation, Chalmers University, Sweden, 1992

[6] "Elavbrottet 23 september, 2003 (Blackout 23 September, 2003)", Report Nr 1:2003, Svenska Kraftnät, 2003-11-03, available on www.svk.se.

[7] ABB Document 1MRK 504 086-UEN, "Technical reference manual, Transformer Protection IED RET670", Product version: 1.1, ABB AB, SA Products, Vasteras, Sweden, (2007).

[8] CRISP Final Summary Report, available at: http://www.ecn.nl/crisp/deliverables/D5.3.pdf

[9] Gajić, Aganović, Benović, Leci and Gazzari: “Using IEC 61850 Analogue GOOSE Messages for OLTC Control of Parallel Transformers”, Sep. 2009, CIGRE Conference on Actual Trends in Development of Power System Protection and Automation in Moscow