ADVANCED OLTC CONTROL TO COUNTERACT POWER SYSTEM VOLTAGE INSTABILITY

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SUMMARY

The main purpose of the automatic voltage regulator (AVR) for power transformers with on-load tap-changer (OLTC) is to keep the voltage on low voltage (LV) side of power transformer within a preset deadband. Originally AVR was designed to compensate for the voltage drop across power transformer impedance caused by flow of the load current. Therefore an AVR shall react and change position of OLTC in accordance with LV side load variations. However, the AVR will as well react on abnormal voltage variations on the high voltage (HV) side of the power transformer. Sometimes such AVR behaviour is not desirable because it just further increases the total load on the HV system (i.e. transmission system). Especially, such behaviour 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 tap-changer control in order to perform properly also during stressed situation in the power system.

Most of the current commercially available automatic voltage regulators (AVRs), just measure the LV side voltage of the power transformer in order to control OLTC 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 AVR 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 OLTCs connected in series and to minimize the overall number of OLTC 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 an on-load tap changer (OLTC). The OLTC 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 tap changers offer between ± 9 to ± 17 steps (i.e. 19 to 35 positions).

The automatic voltage regulator (AVR) is designed to control a power transformer with a motor driven on-load tap-changer. Typically the AVR 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 on-load tap-changer mechanism to move it up or down by one position. The pulse is generated by the AVR 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 OLTC CONTROL PRINCIPLES FOR SINGLE TRANSFORMER

A typical AVR measures the busbar voltage (UB) 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 UB 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 OLTC voltage step. Typical setting is 75% of the OLTC step.

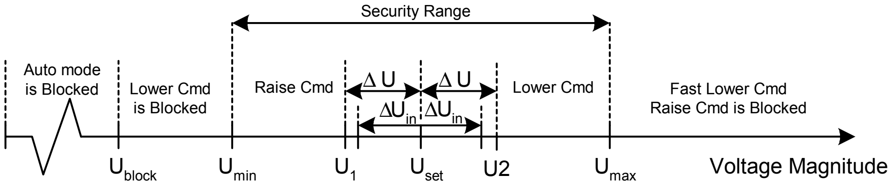

Figure 1: Typical AVR Voltage Scale for Automatic OLTC Control

During normal operating conditions the busbar voltage UB, stays within the deadband. In that case no actions will be taken by the AVR. However, if UB 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 OLTC operations due to temporary voltage fluctuations. The time delay may also be used for OLTC co-ordination in radial distribution networks in order to decrease the number of unnecessary OLTC operations. This can be achieved by setting a longer time delay for AVRs located closer to the end consumer and shorter time delays for AVRs located at higher voltage levels.

AUTOMATIC OLTC CONTROL PRINCIPLES FOR PARALLEL TRANSFORMERS

Automatic On-Load Tap-Changer Control of parallel transformers can be made according to three different methods:

I. Reverse Reactance method
II. Master – Follower method
III. 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 AVRs, 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:

I. Regulate the LV side busbar voltage to the preset target value
II. 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 almost 90^0, whilst transformer T2 circulating current leads the busbar voltage by almost 90^0. 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 optimised 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.

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

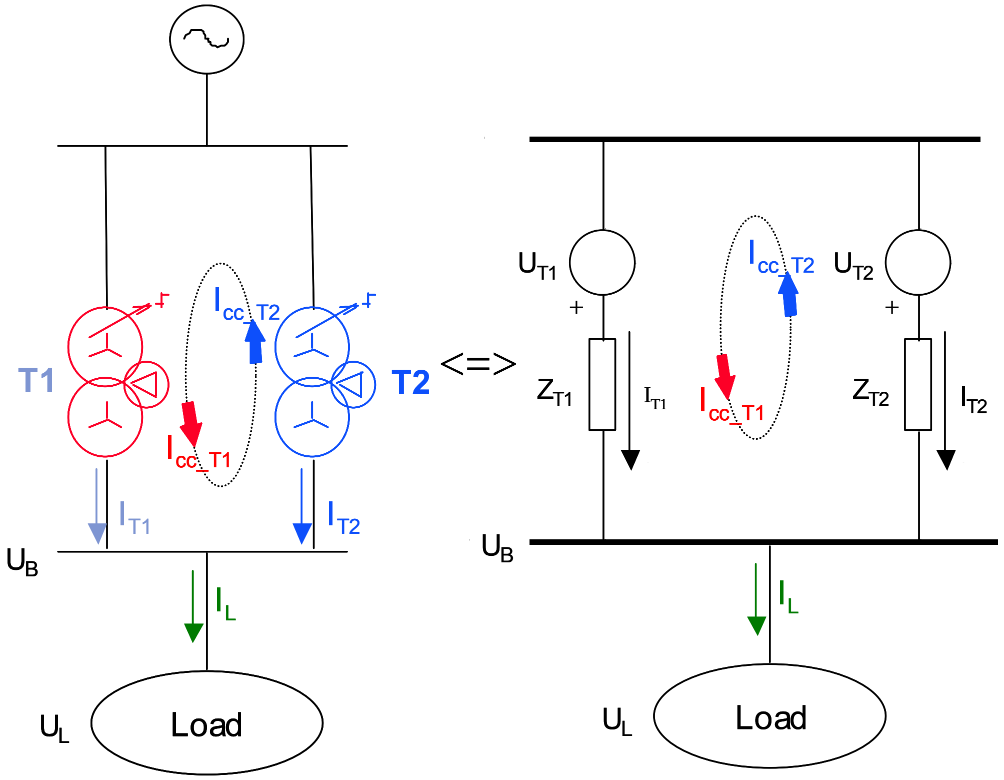

Figure 2: Equivalent scheme for two parallel transformers in accordance with minimizing circulating current method

KNOWN WEAKNESSES OF TRADITIONAL AVRs

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

I. Radial active power flow from HV to LV side is pre-request for correct operation
II. Time coordination of cascading AVRs can be quite difficult task in order to minimize number of overall OLTC operation in a power system and still keep acceptable time delay for AVRs installed closest to the typical loads [4] & [5]
III. 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)
IV. 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)
V. LV side load recovery by AVR action during slow voltage collapse in power system [1]

However in this paper only the problems II. & V. will be addressed.

LESSONS LEARNED FROM SWIDISH 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 tap-changer control in order to perform properly also for disturbed conditions. Figure 3 shows HV side voltage and OLTC position for a power transformer connected between 400kV transmission system and 130kV subtransmission system, in the affected area, at the end of the Swedish blackout in 2003 [6]. The used AVR is designed only to keep the voltage at the low voltage side of the power transformer within certain limits, around the set point.

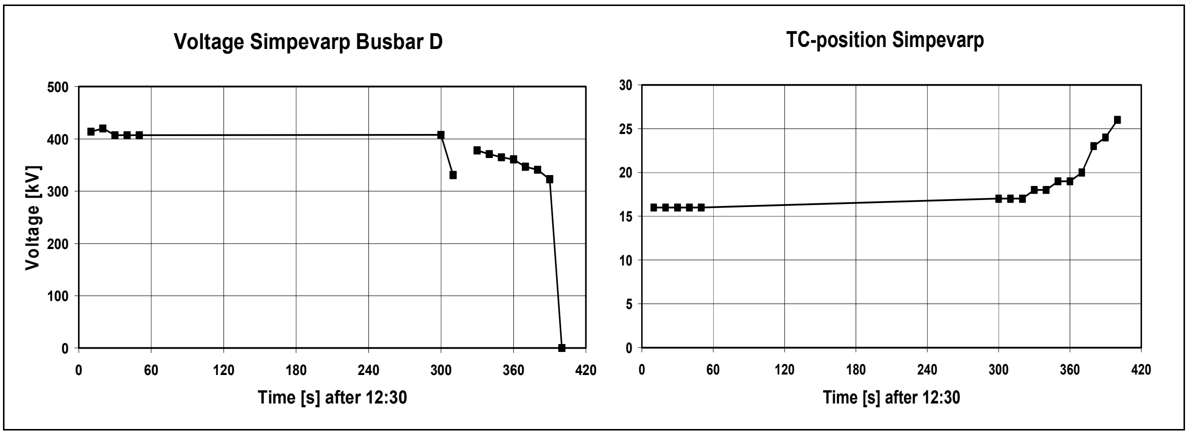

Figure 3: Transformer HV voltage and OLTC position recordings at the end of the Swedish blackout in September 2003

When the transmission side voltage decreases, the tap-changer position is increased by AVR 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 subtransmission voltage – and thereby the load – drawing more active and reactive power from the already weakened transmission system. Similar AVR behaviors have as well been reported during other blackouts, which happened in last 20-30 years all around the world.

ADVANCED AVR OPERATING PRINCIPLES

The main purpose of the automatic voltage regulator for power transformers with on-load tap-changer is to keep the voltage on low voltage side of power transformer within a preset deadband. Originally AVR was designed to compensate for the voltage drop across power transformer impedance caused by flow of the load current. Therefore an AVR shall react and change position of OLTC in accordance with LV side load variations. However, the AVR 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 3. Typically modern commercially available AVRs just measure the LV side voltage of the power transformer in order to make decisions about OLTC 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 4. Additionally the total reactive power flow through the power transformer can be measured as well.

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 undervoltage stages it is then possible to monitor HV side voltage magnitude and consequently influence the operation of the AVR 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 AVR 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 taken:

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

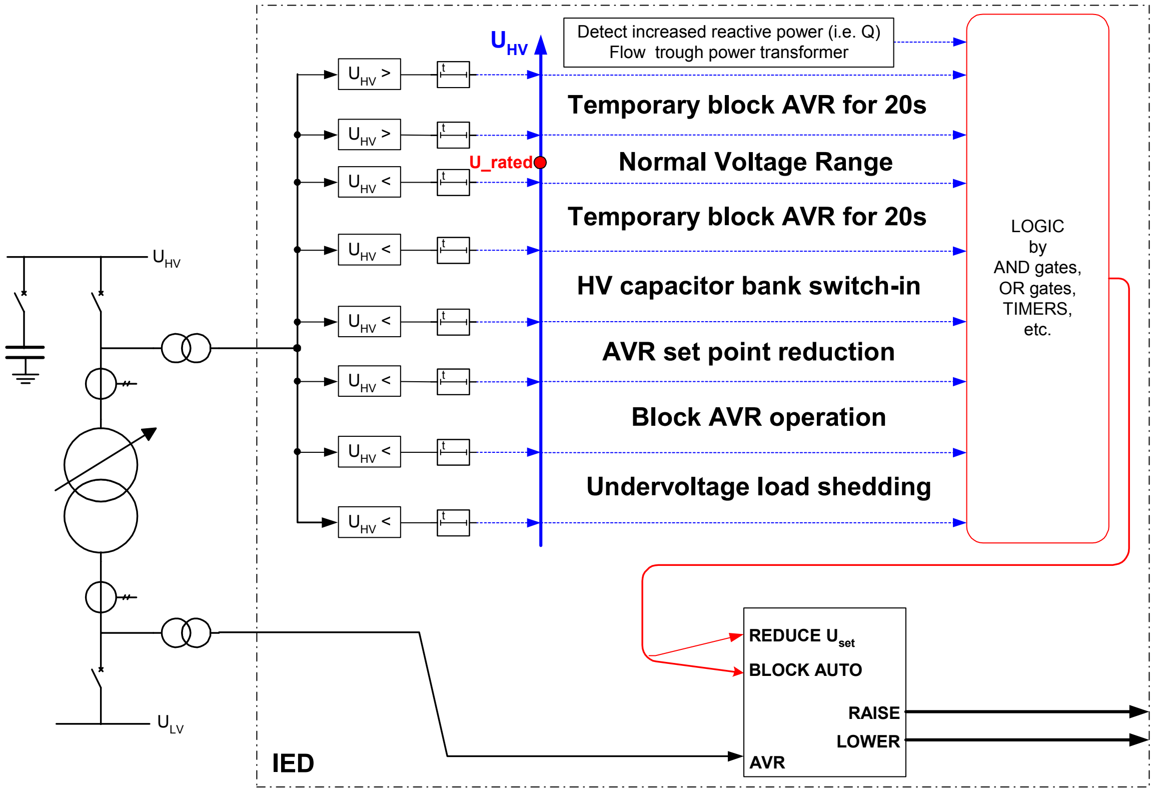

Figure 4: Proposal for an improved automatic on-load tap-changer control scheme.

Temporary block of local AVR for smaller voltage deviation on power transformer HV side can be actually used to drastically improve the cascading AVR 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 AVR. Therefore the local (i.e. downstream) AVR can be temporary block in order to give additional time to the upstream AVR in order to react and correct HV voltage magnitude. By doing so the operating time of all cascading AVRs 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 AVR in case of failure of the upstream AVR. With such approach overall number of OLTC operations in complete power system can be minimized. At the same time this will represent cost benefit for the power utility regarding required OLTC maintenance.

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.

II. AVR voltage set point reduction, in order to keep low voltage profile on subtransmission system and therefore cause reduction of total active and reactive power demand from HV transmission system.
III. Complete AVR block in order to prevent any OLTC automatic operation in order to prevent unwanted AVR operations during stressed condition on the HV side of power transformer.
IV. Finally undervoltage load shedding of pre-selected outgoing feeders on power transformer LV side can be performed in order to try to protect rest of the power system from complete 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 can be tailor made to fulfill strict requirements of any power system operator and characteristics of the individual power system.

CONCLUSIONS

This paper focuses on new possibility for advanced automatic OLTC 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 OLTC can be much improved and in the same time performance of such AVR scheme will be much better during critical situations in HV power system e.g. slow voltage collapse phenomenon.

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SUMMARY OF AUTHORS' BIOGRAPHY

Zoran Gajić was born in Serbia, former Yugoslavia in 1965. He received his Diploma Engineer Degree with honours from University of Belgrade, Yugoslavia in 1990 and GDE in Computer Engineering from Witwatersrand University, Johannesburg-RSA in 1995. Since 1993 he has been working in the area of power system protection and control within ABB Group of companies, where he had various engineering positions. Currently he has a position of Protection Application Senior Specialist with ABB Power Technologies, Substation Automation in Sweden. He is a member of Cigré and IEEE. Currently he is the Convenor for Cigré, Study Committee B5, WG16. Zoran has published numerous technical papers in the relay protection area. His main working areas are computer applications for protection and control of electrical power systems, development of advanced protection algorithms for numerical relays and power system simulation. Zoran is co-holder of two patents.

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. Most recently Dr. Karlsson hold a position as Application Senior Specialist at ABB Automation Technology Products and now he is with Gothia Power. 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.

Mike Kockott was born in East London, South Africa. He graduated with a BSc in Electrical Engineering with honours from the University of Cape Town in 1980. After leaving university he entered into the SA Navy for his two-year period of National Service. After completion of his National Service, he joined Eskom where he worked from the beginning of 1983 until November 1999. His career began at System Operations where he calculated protection settings for transmission system equipment and performed post-fault investigations. He left System Operations as a Senior Engineer and joined the protection design department. At one time he held the position of Design Manager for all feeder related protection schemes. He later moved on to become a Senior Consultant. In 1996 he was appointed as the South African member to Cigré Study Committee 34. On leaving Eskom, he commenced employment with ABB in Sweden in January 2000. He currently holds the position of Protection Application Senior Specialist.