SMART SUBSTATION MV/LV

Jan JIRICKA
E.ON Distribution – Czech Republic
jan.jiricka@eon.cz

Martin KASPIREK
E.ON Distribution – Czech Republic
martin.kaspirek@eon.cz

Libor KOLAR
E.ON Czech Rep. – Czech Republic
libor.kolar@eon.cz

Miroslav ZAHRADKA
Siemens – Czech Republic
miroslav.zahradka@siemens.com

ABSTRACT

The paper deals with the design and operation of a MV/LV substation which is fit out with a distribution transformer with the on-load tap changer. This solution can be used when voltage in the distribution grid varies a lot due to the operation of distributed energy resources.

INTRODUCTION

The supply territory of the company E.ON Distribution in the Czech Republic accounts for approximately 1.5 million customers. The most of them are supplied from low voltage (LV) distribution grid.

Connected DER

More than 1000MW of distributed energy resources (DER) were connected to this distribution grid – see the Fig. 1.

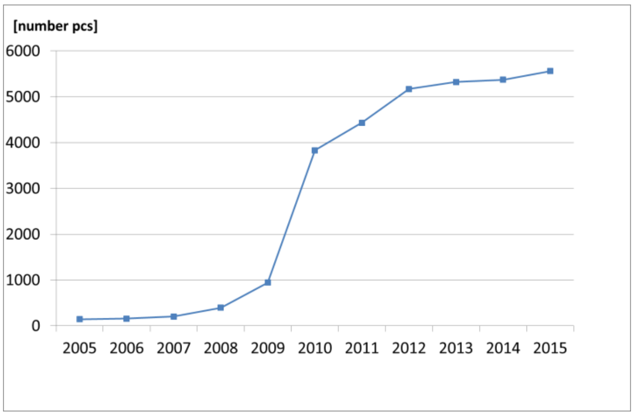

Fig. 1 Number of connected power plants (cumulative)

Impact of DER on voltage quality

The problem with overvoltage was detected in approximately 7 % of low voltage (LV) distribution grids with connected PV plants in 2014 [1] and this problem has to be solved. To cope with the increasing level of distributed generation new solutions for grid operation and new technologies are needed [2]. There is described one solution for voltage stabilization in this paper namely the operation of distribution transformer MV/LV with the on-load tap changer. This proposed solution prevents nonconforming voltage quality (overvoltage) according to the EN 50 160 standard [3] and following investments. Theoretical operation of this regulated transformer was described [4] but practical experience regarding the real operation in the grid is not available.

DISTRIBUTION TRANSFORMERS MV/LV

Distribution transformer with the off-load tap changer

There are operating approximately 18 thousand distribution transformers MV/LV with the off-load tap changer in the distribution grid E.ON in the Czech Republic. When transformer with off-load tap change is used supply interruption is necessary for setting the tap. Setting the tap by means of tap changer is made manually (transformer is in the state without the voltage) when arrival and work of electrician is needed. The tap changer is on the side of medium voltage (MV) and can be set in five positions: -5 %, -2.5 %, 0 %, +2.5 %, +5 % of input voltage which means the regulation range is +/- 2 x 2.5 % of nominal voltage Un.

Distribution transformer with the on-load tap changer

Some producers are able to deliver self-regulating MV/LV transformers or more precisely transformers with the voltage regulation under load. For testing in the distribution grid E.ON in the Czech Republic we choose the type Siemens thanks to its small size, small weight and sufficient regulation range.

producer	Regulation range [% Un]	Weight [kg]
Magtech	- 6.0	2600
Efacec	+/- 4 x 2.5	3950
Reinhausen	+/- 4 x 2.5	2760
Siemens	+/- 3.44	1650

Tab. 1 Some producers of MV/LV transformers with on-load tap changer

REGULATING DISTRIBUTION TRANSFORMER FITFORMER REG MADE BY SIEMENS

The regulating distribution transformer FITformer REG from Siemens can change its transformation ratio under load. This helps energy distributors to stay within the permissible voltage band, without violating the EN 50 160 standard. This is achieved by the transformer's three low voltage (LV) taps which are controlled by control unit. The high voltage tap area for load-free changing of the transformation ratio remains unchanged. The voltage in the medium voltage (MV) network can vary considerably as a result of different operating states. The extremes are known as “heavy load without distributed feed” and “light load with maximum distributed feed”. The challenge for the distribution network operator (DNO) lies in the maximum voltage difference between these two cases. The FITformer REG distribution transformer adjusts the voltage up or down and thereby reduces exceeding of the voltage limits in distribution grid.

The most of DER are connected to the MV and LV distribution network. According to the present standards the operation of power resources can cause maximal voltage deviation 2 % of nominal voltage Un in MV distribution grid and 3 %Un in LV distribution grid. Consideration of the connection to the LV grid is realized independently of power resources operating in MV grid. In case of connected power resources in MV grid and LV grid in the same part of distribution system voltage increase caused by operation of power resources can reach the value 5%Un in relation to LV grid. So when MV and LV grid is respected, overvoltage will occur by operation of DER. The problem with overvoltage caused by operation of DER is not only theoretical but it is supported by voltage quality (VQ) measurements in 30 other distribution LV grids [1]. The current way of grid operation and voltage control is insufficient when distributed energy resources are operating in distribution network. The voltage level in MV and LV grid should not be set fixed already. Voltage in MV and LV grid has to be controlled variable. For variable voltage control in LV grids can be used described distribution transformer, which has interesting principle of tap switching. The circuit consists of vacuum and air break contactors, resistors and a control unit [5]. The principle consists in activating a bypass by closing a contactor. The current then flows over the bypass, in order to ensure a faultless switch over the mechanical vacuum contactor. Thus avoids the occurrence of unwanted voltage peaks or drops even under rated loads during the switch over. The contactor for the bypass gets opened and therefore deactivated after achieving the target position. The switching process is controlled by control unit SIPLUS S7-300. The regulation distribution transformer can be equipped with a communications processor for remote control or monitoring. Therefore the protocols IEC 60870-5-101, IEC 60870-5-104, Modbus RTU and Modbus TCP/IP are available. With this extension the adaptable distribution transformer is capable to be integrated in a smart grid. Thus enables a realization of a regulation based on decentralized measurements in the low voltage grid. The phase voltage is detected in three phases so that the average voltage can be calculated. The voltage is controlled in two stages. Beside the desired rated voltage, values for the voltage limits for slow and fast switch-over can be entered as parameter. The control system is selectively matched to various network conditions by setting the delay time. All values can be freely parameterized separately for the upper and lower limits.

SMART SUBSTATION JAROHNEVICE

Two substations for the distribution transformer FITformer REG were chosen, one of them is called Jarohnevice. This outdoor substation is connected to the MV distribution grid with some connected renewable energy resources (PV plants) so that the voltage in the MV grid varies. So the transformer was installed into this substation in June 2013. This transformer has following technical parameters:

- Nominal power: 400 kVA
- Side of medium-voltage (nominal voltage): 22 kV
- Side of low-voltage (nominal voltage): 400 V
- Taps on the MV side: +/- 2.5 %, +/- 5 % (switchable when de-energized)
- Taps on the LV side: +/- 3.44 % (switching under load)
- Length x width x height: 1,240 x 850 x 1,405 mm
- Impedance voltage: 4 % +/- 10 %

Design and description of the substation

The substation Jarohnevice was additionally equipped with the box DOM 9131 G1 for communication and with the phase-phase voltage transformer VPT 25 for measuring on medium voltage side. The transformer is equipped with the control unit CPU314C-2PN/DP which is used for getting of measured values. The service GPRS and communication unit RTU7M-5 made by Elvac company are used for remote control. The unit RTU7M-5 is inserted in the box DOM 9131 G1. This box is placed next to the low voltage switchboard. Communication protocol IEC 60870-5-104 is used. Distribution transformer can be so controlled and monitored locally (by connecting with the computer by means of the ethernet connection) or remote from dispatching.

date	time	Uset (V)	Tap No.	$UL1_{LV}$ (V)	$UL2_{LV}$ (V)	$UL3_{LV}$ (V)	$UL12_{HV}$ (kV)
2.9.2013	13:33:00	236	2	240,02	239,75	239,97	22,98
2.9.2013	13:36:00	236	2	240,47	240,57	240,53	23,04
2.9.2013	13:39:00	236	2	242,25	242,54	241,91	23,24
2.9.2013	13:42:00	236	2	243,58	243,27	242,93	23,32
2.9.2013	13:45:00	236	1	235,11	234,48	234,69	23,36
2.9.2013	13:48:00	236	1	235,17	235	235,27	23,41
2.9.2013	13:51:00	236	1	235,17	235	235,27	23,33
2.9.2013	13:54:00	236	1	232,45	232,84	233,09	23,17

Tab. 2 Some operating values transmitted in SCADA

The state of the tap is signalized and the number of operating cycles is calculated by control unit. But state of the tap depending on time is not available. So the state of the tap is transmitted to dispatching where it is recorded and archived in the system SCADA – see Tab. 2. The transformer gives some measured data so no additional power analyzer is needed for the monitoring of voltage.

Fig. 2 Substation MV/LV Jarohnevice with the transformer FITforemer REG

Setting of the transformer

Values for the voltage limits for slow and fast switch-over can be entered as parameter. For example the voltage value on the output of the transformer can be set in range from 208 V to 252 V. If the transformer is set according to the Fig. 4 and the voltage increases slow the value of 236 + (0.6*3.44*2.3) = 240.7 V for a longer time then 600 s (without decreasing of this value) then the tap goes down and the voltage decreases about 3.44*2.3=7.9 V, when 230 V is the nominal grid voltage (2.3 V is 1 % of the nominal grid voltage) and 0.6 is the constant respecting 60 % of the limit to step tap down slow (see the Fig. 3). The transformer can run in two modes. In the automatic mode is the tap changed according to the actual measured voltage values in relation to entered parameters. In the manual mode the tap can be set fixed without regard to entered parameters. So you can operate the FITformer as a standard distribution transformer with the fixed set transformation ratio, when needed.

Description	New value	Active value	Min. value	Max. value	Unit
Nominal secondary voltage L-N		236	208	252	V
Upper tapping secondary side		3.44	1	10	%
Lower tapping secondary side		-3.44	-10	-1	%
Limit to step tap up slow		80	55	80	%
Limit to step tap up fast		95	85	95	%
Limit to step tap down slow		60	55	80	%
Limit to step tap down fast		95	85	95	%
Delay time to step tap up slow		600	1	999	s
Delay time to step tap up fast		10	1	10	s
Delay time to step tap down slow		600	1	999	s
Delay time to step tap down fast		10	1	10	s

Fig. 3 Example of setting the voltage limits in the automatic mode

Measurements

Many voltage quality measurements were carried out on the output of the transformer to find an optimal setting of the transformer and to analyze the benefit of voltage variations. When voltage increases a lot then the tap goes down. After decreasing of the voltage it grows still, then the voltage decreases and the tap goes up again. The increasing of the voltage after its decreasing is the transformer's benefit of voltage variations. The benefit of voltage variations is bigger in the grid (for example at the end of the LV feeder) than in the substation (on the output of the transformer) when some distributed energy resources are connected in this grid.

The transformer's benefit of voltage variations is approximately 1 % of nominal voltage (2.3 V) but the tap is 3.44 % of nominal voltage. The benefit of voltage variations (in one direction) is practically always less than the tap due to setting of dead bands.

SMART SUBSTATION DRAHANY

The distribution substation in Drahany was chosen because of the significant influence of renewable energy resources installed and connected in MV grid and additionally also due to size of the voltage differences on each phase in LV grid. The substation is equipped with regulated transformer FITformer version 2.0 able to regulate under the load. Regulation is based on solution developed and implemented by Siemens using smart metering approach measuring voltage levels in LV grid by installed smart meters. Measured voltage data are delivered to substation where the calculation algorithm evaluates delivered values and calculates the tap position of the distribution transformer. Such system of voltage control was installed and commissioned in April 2015. The principle of regulation is described in Fig. 4.

The main difference between the FITformer version 1.0 and 2.0 is the way how the control cabinet with the control unit is mounted inside or separately outside the transformer. Installation outside brings great benefit to access the control system without necessity to shutdown the transformer and interrupt delivery of electricity to final customers.

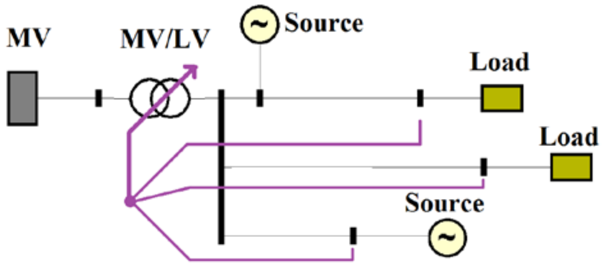

Fig. 4 The principal of voltage regulation

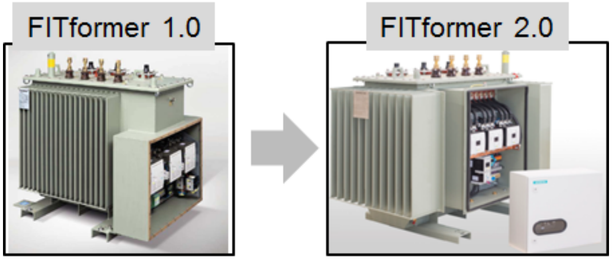

Fig. 5 FITformer versions 1.0 and 2.0

Design and description of the substation

The principle of our LV grid regulation system in substation Drahany is based on 10 pieces of 3-phase smart meters Siemens AMIS TD-3511 installed in strategic places of the grid. Smart meters are delivering measured data through the PLC communication to the data concentrator (DC) in the substation. The data concentrator joins together also the communication with the SCADA system, RuggedCom industrial PC and the FITformer. Transformer's control is based on voltage values from meters evaluated by complex analysis of control algorithm hosted in the Siemens industrial PC RuggedCom (RC). There is also possibility to control the transformer remotely; in such case E.ON installed Elvac RTU providing measured data to SCADA system and on the other way round handling control command from SCADA towards the transformer. In case of service activities additional remote access through the GPRS modem is available for Siemens.

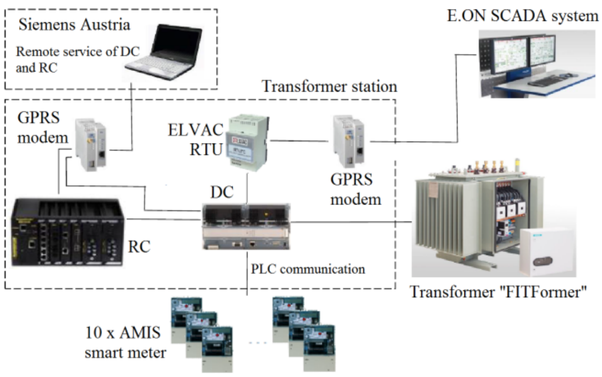

Fig. 6 Logical architecture of the regulation

The software architecture of the control solution running in RuggedCom industrial PC is described in the Fig. 7.

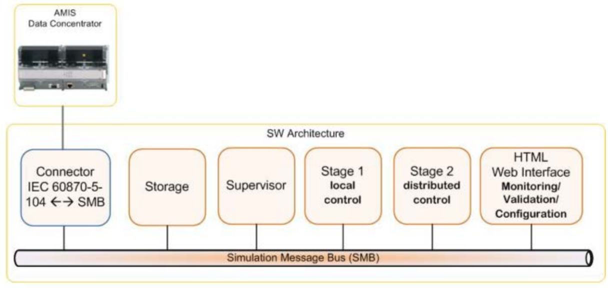

Fig. 7 Solution software architecture

Voltage control solution settings

Control of the voltage regulation is assured by main and backup algorithms. The backup algorithm (Stage 1) regulates the transformer tap position only based on values measured directly at the substation MV/LV. Such control stage is in operation only if the condition of sufficient amount of measured data from smart meters is not fulfilled. This can be caused e.g. by communication issues between the smart meters and data concentrator. The principal of the stage 1 algorithm including the explanation of used parameters set value, deadband and time factor is described in following Fig. 8.

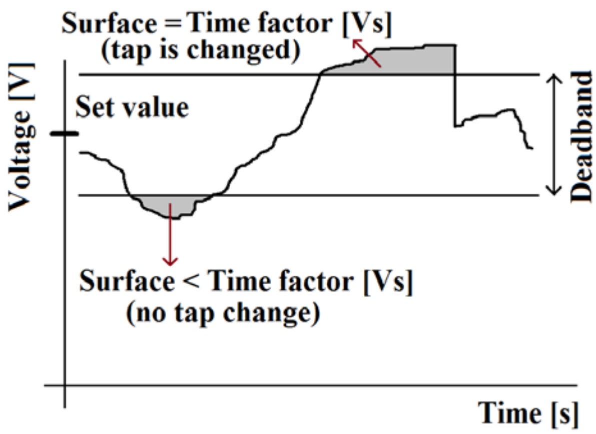

Fig. 8 The principal of Stage 1 control algorithm

The main control algorithm (stage 2) functionality requires measured voltage values from all 3 phases collected in smart meters installed in the LV grid. Based on such data evaluation, the maximal and minimal voltage values of the grid are defined and used in case of switching appropriate tap position in the transformer. Input parameters of the control stage 2 are the upper voltage limit, lower voltage limit, time factor and tap hysteresis. Time factor parameter defines the delay of the tap control after exceeding the voltage level threshold. Tap hysteresis together with the size of the transformer tap arrange not to cause undervoltage in the LV grid during handling the situation with overvoltage.

SMART SUBSTATION VELENICE

Distribution substation Velenice was selected for the test of GRIDCON regulated transformer from Maschinenfabrik Reinhausen. In first phase of the selection the GRIDCON does not fulfill our conditions for operations within the distribution grid of 22 kV, anyway after implementing of several changes on the vendor side it was finally possible to install it in our grid.

Design and description of the substation

The transformer is regulating according the voltage values measured directly at the substation. Tap switching parameters are the following:

- Nominal power: 400kVA
- Side of medium-voltage (nominal voltage): 22 kV
- Side of low-voltage (nominal voltage): 420V
- Taps on the MV side: +/- 2.5 %, +/- 5 %, +/- 7.5 %, +/- 10 % (switching under load)
- Length x width x height: 1,260 x 850 x 1,605 mm
- Total weight: 2380 kg
- Impedance voltage: 4 % +/- 10 %

Fig. 9 Transformer GRIDCON, substation Velenice

GRIDCON regulated transformer is in standalone operation without providing any data towards the SCADA system. Functionality of the transformer is monitored through the installed voltage quality measurement. Control of the transformer in case of selecting the right tap position is handled via its own control unit inside the control cabinet of the transformer, which is placed inside the cabinet of the substation.

Setting of the transformer

Voltage regulation algorithm is configured through several variables like desire voltage value, bandwidth, delay time and quick return threshold.

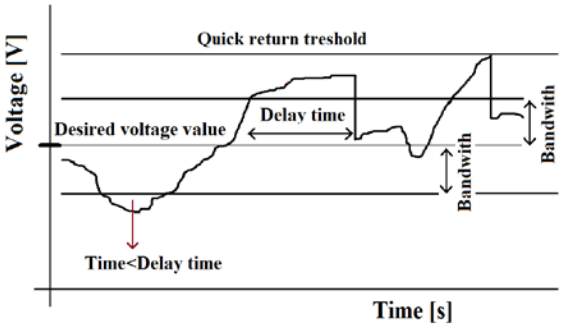

Fig. 10 The principal of the voltage regulation algorithm

SUMMARY

MV/LV regulated transformers under load can be operated in two modes of control. If the control is depending on the voltage at the substation, the regulated transformer is only able to mitigate fluctuations in the MV grid. When the control is using voltage values measured in the LV grid, the transformer with the suitable regulation approach can also influence the voltage variations due to present power flow. Regulated transformer itself is a relatively new element installed in distribution grid which is currently being tested mostly in pilot installations. Based on the evaluation of the pilot installations, it probably would be possible such new regulatory elements incorporate to the standard distribution system equipment.

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