Impact of Characteristics of Block-Transformers on Inrush Currents and Voltage Distortions at the Connection Point of Wind Parks

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Abstract —**In the procedure of connecting large wind parks (WP) to the external power grid, TSO's or DSO's request is that WPs in operation do not excessively affect the power quality in the connection point. In the process of determining WP operating procedures it is necessary to include switching operations in the WP main feeder. The transformers connected near the wind generator units are then energized and a transformer inrush current appears, followed usually by voltage distortions. Those currents may cause nuisance tripping of protection devices and power quality problems in the WP connection point. For illustration, the connection to a real power grid of a large WP with twelve generators and block transformers is simulated. Considered network short circuit power is comparable to typical parameters of the transmission or distribution medium-voltage networks. Simulated inrush currents depend on the characteristics of connected devices in the network. Results of our study can be useful for correct protection relay device setting and determining optimal WP exploitation procedures.**

Keywords: Wind park (WP), inrush currents, UMEC model, PSCAD simulation, voltage distortion.

I. Introduction

In majority of Grid Codes for connection of distributed generation (DG), allowed voltage variations in connection points with external grid are limited (usually to 6%). From different wind parks (WP) exploitation experience, it is known that switching operations of the main feeder's circuit breaker can cause considerable voltage distortions. Moreover, if most of block-transformers near wind generators are not disconnected form the grid at the moment of switching, inrush currents can cause nuisance tripping and further power quality problems in point of connection of considered wind park. The reason for determining the inrush currents which can occur in grid-connected WP is to avoid unwanted problems with switching operations.

Contemporary power system simulation applications use UMEC (Unified Magnetic Equivalent Circuit) model for power transformers modeling, which consider physical characteristics of power transformer (exact magnetizing curve, winding geometry etc.). Such model is suitable for inrush phenomenon studies [1] and will be used in WP switching procedure simulation cases - connection of a large WP composed of twelve generators with installed power of 21.6 MVA with belonging block-transformers (2 MVA each). Different switching cases and topologies are considered along with consideration of the type of main WP feeder (overhead line or underground power cable).

II. Simulation of Switching Operations of the Power Transformer

A. Transformer connected to ideal voltage source

Connection of power transformer to the external grid i.e. switching of the circuit breaker on the high-voltage side, often is followed by appearance of inrush currents. These currents are characterized by amplitudes which abruptly reach very high levels in the first half of the base period [1]. Also, inrush currents cause voltage distortions in busbars in the point of common coupling (PCC) of the considered wind park. Amount and duration of inrush currents depends on phase angle of external grid voltage in the switching-on moment, on non-linear magnetizing curve of the power transformer and amount of remanent magnetism in the core of the power transformer [1], [2].

For the illustration of inrush currents phenomenon an EMTDC simulations with UMEC transformer model are performed. A power transformer with rated data S=2MVA; u_k=6%, 0.69/35 kV, YΔ, is considered and is connected to ideal voltage source. Selected transformer's rated data are typical for the block transformers for wind generators. Configuration of the simulation setup is presented in the Figure 1.

Waveforms of the transformer's inrush currents during the switching on ideal 35 kV voltage source are presented in the Figure 2.

For modification of the switching-on angle, i.e. moment of switching of the CB on the primary side of the voltage transformer, the control logic of EMTDC is used (Figure 1).

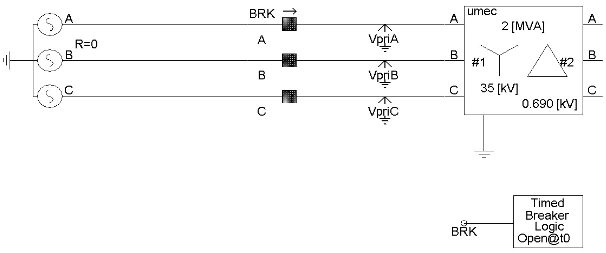

Figure 1: Typical WP installed power distribution by standard voltage levels.

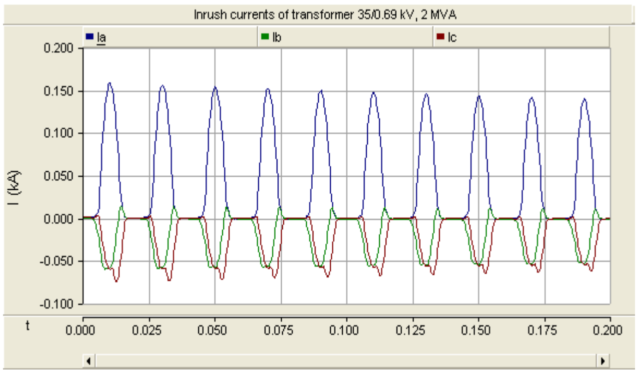

Figure 2: Inrush currents in power transformer 2 MVA during switching on ideal 35 kV source (switching on angle =0°)

Default magnetizing curve parameters for UMEC three-limb model is used with magnetic curve parameters [4]. Changing the switching angle, we can obtain graph of inrush currents against switching-on angle, as presented in Figure 3 for phase A.

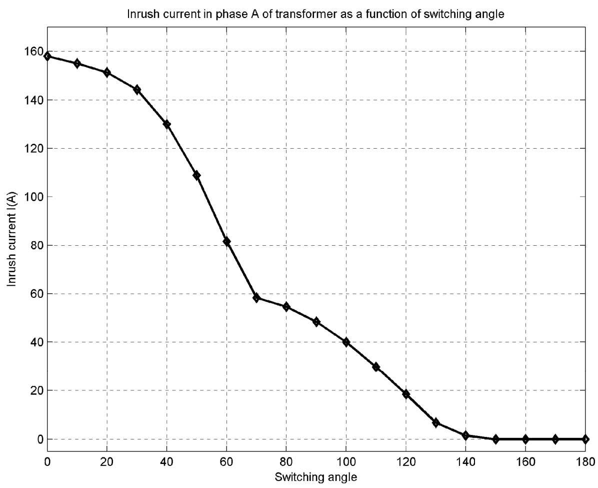

Figure 3: Inrush currents as function of switching-on angle (phase A)

Presented graph values are obtained without taking into account of power transformer's remnant magnetism in the core.

B. Connection of power transformer with remnant magnetism in the core to ideal voltage source

Inrush currents in the power transformers can reach even higher values if switching-on of the circuit breaker in the high voltage side is performed in presence of remnant magnetism in the transformer's core. There are proven methods for simulating this phenomenon shown in [1], [4]. Level of remnant magnetism in the core is determined using conditions during the switching-off process [4]. One way to simulate the occurrence of remnant magnetism in power transformer is introducing controllable sources of DC current in the circuits of the primary transformer's side. Simulation is performed with primary side circuit breaker in "off" position and with connected DC current sources in every phase of primary circuits of a power transformer. Using this procedure, the effect of remnant magnetism is obtained as in [4], using the simulation setup presented in Figure 4.

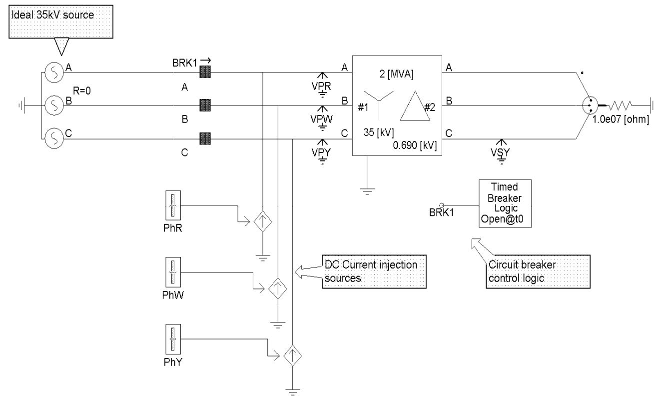

Figure 4: Simulation setup for determining inrush currents in a power transformer 2 MVA during switching on ideal 35 kV source (switching on angle =0°)

For determining exact levels of DC currents for simulation of remnant magnetism effect, we need to know the exact magnetizing flux curve and magnetizing currents of considered power transformer. The best way is to obtain curves and magnetizing currents directly from manufacturer's measurements. Otherwise, these curves and currents can be determined with simulations or measurements as presented in Figure 5.

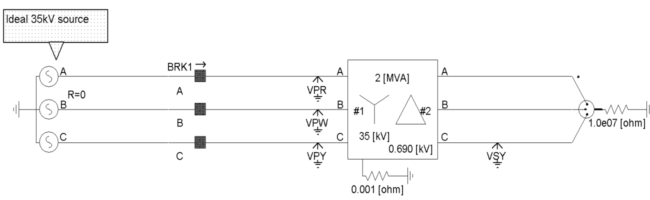

Figure 5: Simulation setup for determining inrush currents in a power transformer 2 MVA during switching on ideal 35 kV source (switching on angle =0°)

Using this procedure we can obtain magnetizing currents *Im* for peak values of the magnetizing flux curve. Furthermore, in the main simulation procedure these *Im* currents are used for simulating remnant magnetism phenomenon. In one phase of primary circuit of selected power transformer we inject +80% of *Im* and in the other two phases -40% of *Im* [4]. Amounts and duration of inrush currents in the power transformer depends on the phase angle of the grid voltage primary side where the transformer is switched on and on the level of remnant magnetism in the magnetic core. This voltage angle can be varied using the switching logic by selecting exact CB switching moment [7]. Currents wave shapes are similar as in the case of switching on transformer without remnant magnetism, but the levels of inrush currents amplitude are much higher. As presented in Figure 6, we can measure about 485 A for switching angle of 0° in phase A.

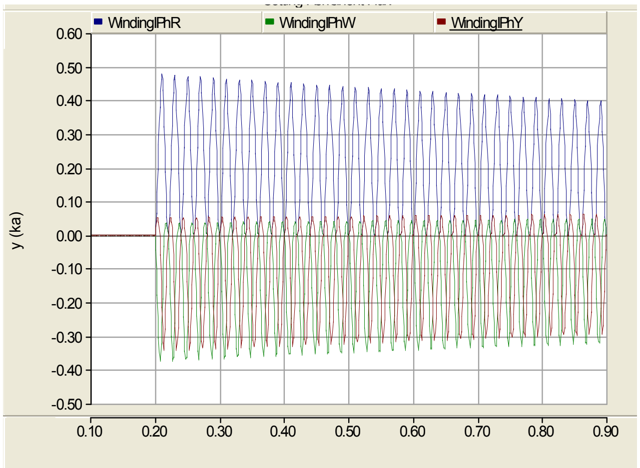

Figure 5: Currents in power transformer 2 MVA during switching on ideal 35 kV source (switching on angle =0°)

Magnetic fluxes in windings of power transformer during occurrence of remnant magnetism in the core are presented in Figure 6.

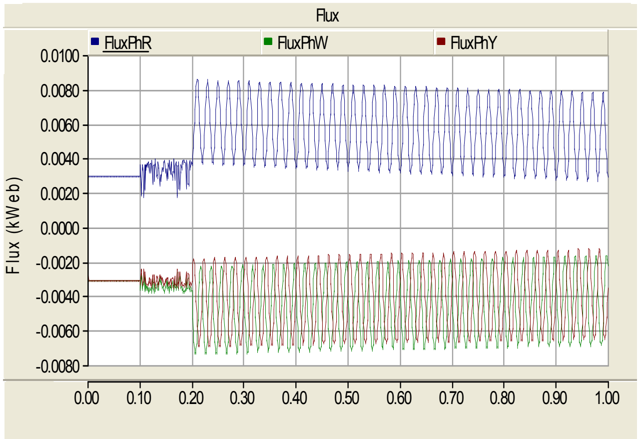

Figure 6: Fluxes in power transformer 2 MVA during switching on ideal 35 kV source (switching on angle =0°)

Obtained values will be used in the simulation of a realistic case of connecting WP to the external distribution network.

III. CASE STUDIES

A. *Configuration and objective of simulation*

An example of a wind park with 21.6 MVA installed power is presented in Figure 7. Wind park installation consists of twelve wind generators with block-transformers. All high-voltage sides of block-transformers are connected to a 35 kV busbar of WP substation. Main feeder of WP substation is connected to the nearest substation of the system. Common convention is that junction point is named as Point of Common Coupling (PCC) [5], [6]. Topology presented in Figure 7 is common for relatively large WP [7]. However, exploitation procedures for considered WP must be so defined that power quality parameters are kept within defined ranges.

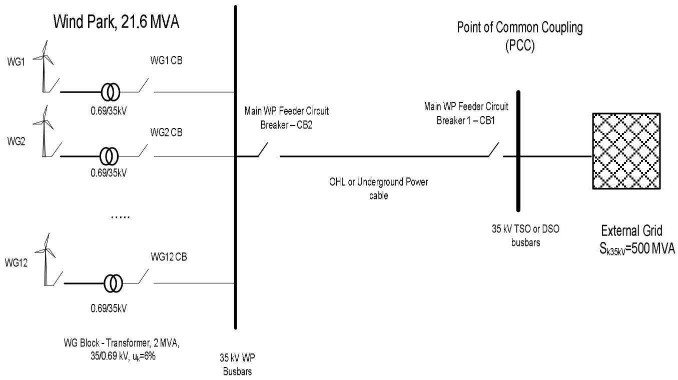

Figure 7. Configuration Scheme of WP connection on Distribution Operator 's 35 kV substation

For that reason, it is necessary to assess the inrush currents in the main feeder and voltage distortions on PCC busbars which could be caused by switching on of block-transformers.

B. *Simulation results*

Short-circuit power in the PCC is an extremely important parameter which determines the voltage stability at the PCC and the natural ability of the power system to absorb faults. Large wind parks are usually installed in the rural areas where short-circuit powers in the PCC are relatively small [6]. Real values of short-circuit power in medium voltage networks where WPs are usually connected are about 500 MVA. This value was assumed in simulation case which is implemented in PSCAD/EMTDC according to the Figure 7. The type and impedance of the main feeder plays the role in overall configuration as well. There are differences in results if the main feeder is an XLPE underground cables or OHL for the same cross-section [8]. Finally, applied model for block-transformers is UMEC model described in II.A.

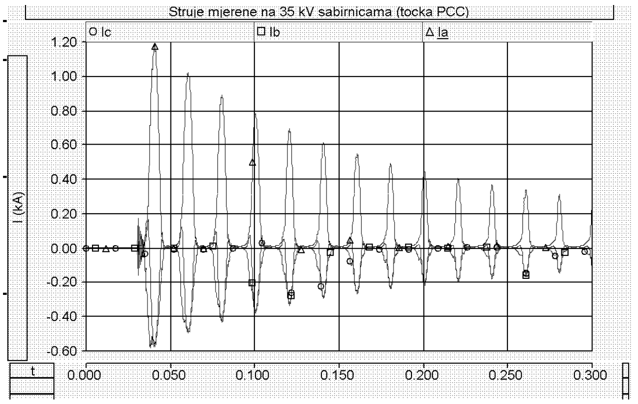

Figure 8. Inrush currents in the main WP feeder when simultaneously all twelve block – transformers are switched on (Main feeder - XLPE cable 150 mm2, 5 km length)

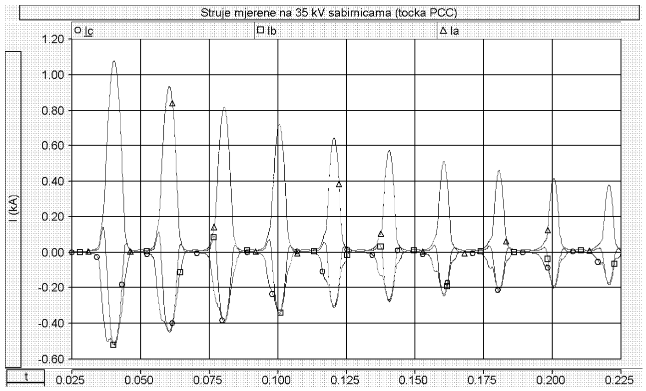

Figure 9. Inrush currents in the main WP feeder when simultaneously all twelve block - transformers are switched on (Main feeder - OHL 150 mm2, 5 km length)

For the XLPE underground cable as main WP feeder, the maximum inrush current of considered installation is 1,18 kA in the phase A. When the main WP feeder is OHL (with the same cross section - 150 mm^2.), the maximum amplitude of the inrush current is 1.08 kA.

IV. VOLTAGE DISTORTIONS IN THE PCC OF A WIND PARK

Grid codes in countries with considerable amount of installed distributed generation define the allowed voltage distortions in the point of common coupling (PCC). In majority of grid codes that amount is up to the 6% of rated voltage [5]. It is well known that higher short-circuit power in the PCC means higher ability of power grid to absorb faults and voltage deviations. We considered a realistic value of short-circuit power of SSc35kV=500 MVA in the 35 kV busbars at PCC, and we calculated inrush currents of all twelve simultaneously switched-on block-transformers near wind generators. It caused voltage distortions well above the limit. (Figure 10).

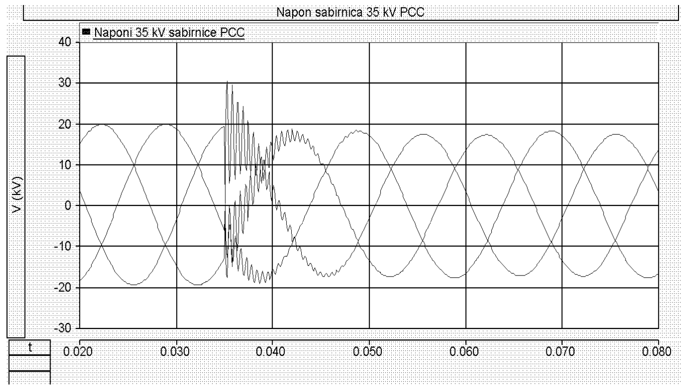

Figure 10. Voltage distortions in the PCC. Simultaneously all twelve block - transformers are switched on

Consequently, we observed that inrush currents can reach the range of fault currents. Obviously, to avoid malfunction of the WP system, it is necessary to find the correct switching-on sequence for the considered large WP. Such a sequence must be acceptable for WP owner as well as distribution operator and must assure that power quality stays in the allowed range. In the Table I are presented values of voltage distortions in p.u. (in the relation to the rated voltage) as a function of the number of simultaneously switched-on block transformers of WG units. As before two main cases are simulated and considered - when main WP feeder is a XLPE underground power cable (150 mm^2) and OHL (also 150 mm^2).

TABLE I. VOLTAGE DISTORSIONS AT PCC

Number of simultaneous switched on WP block-transformers	Voltage distortion in PCC (Main feeder XLPE Und power cable 150 mm^2)	Voltage distortion in PCC (Main feeder OHL 150 mm^2)
1	1.73 %	1.75 %
2	3.45 %	3.36 %
3	3.34 %	3.38 %
4	5.10 %	4.90 %
5	6.62 %	6.35 %
6	6.64 %	6.36 %
7	6.75 %	6.36 %
8	6.78 %	6.37 %
9	6.65 %	6.37 %
10	6.75 %	6.37 %
11	7.14 %	6.42 %
12	8.207 %	7.75 %

Large WP are mostly installed in rural areas where short-circuit powers are usually low [5]. Here we have chosen a relatively small short-circuit power (500 MVA). For that reason, for only three simultaneously switched-on block transformers we get a voltage distortion of 3.34 % in the PCC. It is very important to know the value of short-circuit power in the PCC which can be dependent on high-voltage apparatus parameters [8] [9]. Also, for every installed WP we must know the exact characteristics of block-transformers connected to

WG units for defining exact exploitation procedures (allowed number of simultaneously switched block-transformers etc.). For here considered example, the exact procedure can be defined from the results presented in Table I. In the above example four block-transformers would be allowed to switch-on at the same time. With such approach, allowed voltage deviation will be in the allowed range of usually prescribed 6%.

V. INRUSH CURRENTS CAUSED BY SWITCHING OF POWER TRANSFORMERS WITH REMNANT MAGNETISM IN THE CORE

When the remnant magnetism is present in the block-transformers of wind generator units, the values of inrush currents can reach fault-level values [2]. For that reason in the following simulations for defining the exploitation scenarios it is necessary to consider the remnant magnetism. The procedure for simulate the remnant magnetism using DC current sources is described in II.B. In Figure 11 the inrush currents obtained for example case configuration are presented. The remnant magnetism influence is simulated for three of twelve block-transformers (Figure 7) in this case study.

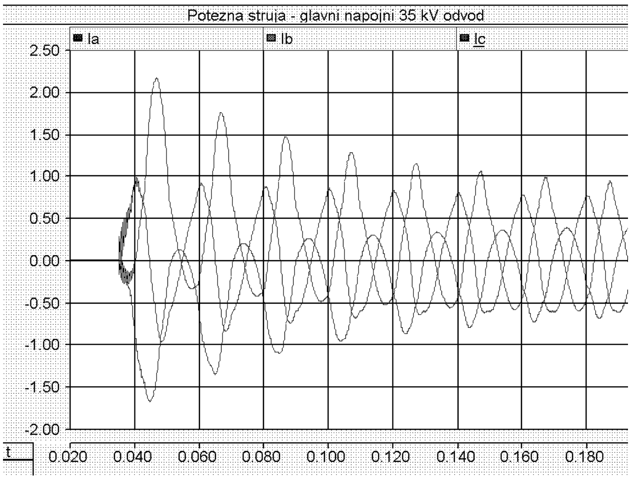

Figure 11. Inrush currents on the main WP feeder . Simultaneously all twelve block – transformers are switched on where 3 of them have remnant magnetism in the core.

High inrush current on the main WP feeder is evidently in the fault range (I=2.16 kA). Such amount of inrush current can cause tripping of protection devices. Also, the considered switching case causes considerable voltage deviation in the PCC busbars. For that reason it is imperative that we consider the remnant magnetism in defining the exploitation procedures of large wind parks.

CONCLUSION

From the obtained simulation results, it can be concluded that switching on of all block-transformers of wind generators at the same time can lead to many problems in the power system operation (unwanted tripping of protection devices, voltage distortions at the PCC etc.). Furthermore, obtained simulation results and waveforms can be used for protection relays setting as well as for defining WP exploitation procedures. For obtaining of exact simulation results it is necessary to know the exact characteristics of the high-voltage apparatus, especially of block-transformers of wind generator units. Applied UMEC model for power transformers modeling allows exact calculations which were validated by field measurements. For defining the exploitation scenarios of WP operation, the phenomenon of remnant magnetism of power transformers must be considered. The maximum number allowed of simultaneously switched-on block-transformers will be a direct conclusion from such analysis, as well as other important parameters (parameter settings for protection relays, expected inrush currents, estimating of voltage distortions, etc.)

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