ENERGISING INRUSH CURRENT TRANSIENTS IN PARALLEL-CONNECTED TRANSFORMERS

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ABSTRACT

When there is integration of wind farm into the power system network, it is vital to check the effect of the transients' stability. The transient interaction between the transformers affects the magnitude and duration of the sympathetic inrush current. This has become a significant issue for medium or large transformers. System study of the inrush caused by energisation of parallel-connected transformers connected to distribution networks are discussed in this paper. It is carried out via PSCAD modelling of a switching study of the energisation of the transformer between two and three transformers and validated using laboratory experiment. Several different switching scenarios are implemented and their transient characteristics are compared.

INTRODUCTION

In any electrical supply network, its stability and reliability are the most important concerns. One of the issues that could pose a problem is the voltage and current disturbance triggered by energisation of power transformers installed in transmission and distribution networks. This is already a well-known issue for a long time. Nevertheless, it is now becoming more significant due to two things: electricity markets evolved to an increased number of participants with frequent changes in the network topology, and the continuing shift in generation towards renewable sources which are inherently intermittent. This has led to the possibility of a substantial increase in number of switching operations and thus making the issue of switching transients even more relevant [1].

Of particular interest is the transient stability in wind farms. This is because electricity generation from wind turbines has been expanding rapidly worldwide [2] and becoming the focus of many research and development activities of late. The issue of transient stability becomes more pressing since wind power penetration is increasing rapidly, yet the financial constraint has caused electric utilities to build power systems with less redundancy and operate them closer to transient stability limits. A recent report by the International Council on Large Electric Systems (CIGRÉ) [1] emphasised significant need for study and awareness from the power systems engineers of potential problems from transformer energisation especially from wind farms, as each wind turbine generator is accompanied by its transformer and it may generate complex sympathetic interactions.

Energising inrush transients in parallel-transformers energisation can cause various serious power system issues such as sympathetic inrush current phenomenon, harmonic resonance over-voltages, excessive mechanical and electrical stresses, mal-operation of the protection relays and also voltage sags.

Past research has investigated the magnetizing and sympathetic inrush phenomenon itself, the modelling, the adverse effect caused by this phenomenon and also the counter-measures [3-5]. However, there has been little attention paid to this problem in connection to renewable distributed energy resources. Since wind farm grids normally comprise a large number of parallel wind turbines with associated transformers, the study of sympathetic inrush is important for the reliable operation of this system. Moreover, previous research focused primarily on modelling and simulation. Thus further laboratory investigations would be valuable to compare the accuracy of the model used for predicting the sympathetic inrush phenomenon.

In this paper, a detailed PSCAD model is developed to study the energisation of parallel-connected transformers. Next, parallel-connected transformers between wind turbines are investigated. Note that in a typical wind farm, every wind turbine is paired with a step-up transformer before connecting to the common grid. The paper will discuss the energisation of parallel transformers and measurements of inrush current transients are performed on same rating distribution transformers. The laboratory setup and the measurement procedure will be described.

SYMPATHETIC INRUSH

Sympathetic inrush current transient can occur in parallel-connected transformers in which one or more transformer is already in operation. When an un-energised transformer is switched into service, the transformer(s) that are already in operation will go into saturation. This phenomenon is called sympathetic inrush. This transient will change the duration and the magnitude of the transient magnetising currents in the transformers involved.

Sympathetic Inrush Transients in Parallel-Connected Transformers

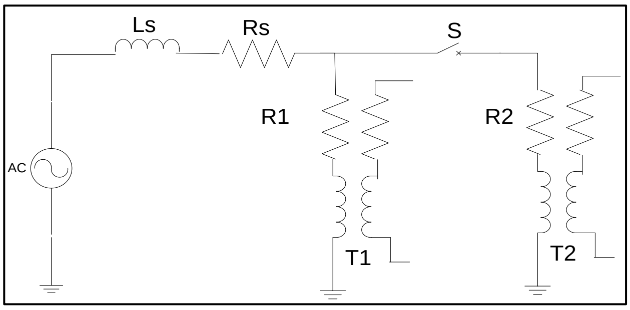

Figure 1 Circuit for parallel-connected transformers

The circuit of Fig. 1 is utilised to facilitate further understanding of sympathetic inrush transients in parallel connected transformers. Here, *AC* denotes the emf voltage, L_s and R_s denote system inductance and system resistance respectively. *T1* and *T2* denote transformer 1 and 2 which include internal winding resistances *R1* and *R2*. *S* represents the switch.

By referring to Fig. 1, it can be seen that only the magnetising current of *T1* flows through the system impedance from source to transformer [6]. Then when *T2* is energised, a transient inrush current is drained from the emf voltage, which flows through the system. As the flux in a transformer is proportional to the integral of the voltage waveform at the transformer terminals, the flux generated in the transformer *T1* and T2 respectively are:

$$\Delta\lambda_1 = \int_t^{t+T} [(R_s + R_1).i_1 + R_s.i_2].dt \quad (1)$$

$$\Delta\lambda_2 = \int_t^{t+T} [(R_s + R_2).i_2 + R_s.i_1].dt \quad (2)$$

where $\Delta\lambda_1$ represents the flux change in a cycle for the *T1* and $\Delta\lambda_2$ represents the flux change in a cycle for *T2*.

At one point, $\Delta\lambda_1$ will reach zero and i_1 will stop increasing which results in the following expression for i_1 within that particular cycle:

$$i_1 = -\left[\frac{R_s}{R_s + R_1}\right].i_2 \quad (3)$$

From equation (3), it can be seen that the system resistance, R_s plays a key role in the interaction between the two transformers. R_s keeps both *T1* and *T2* saturated in alternate half cycles, with the currents i_1 and i_2 causing the effect of the transformers saturation. The transient currents i_1 and i_2 remain for a prolonged time.

Sympathetic Inrush in Wind Farms

Sympathetic inrush transient is also observed in transformers for wind farms [7]. In wind farms, it is not unusual that several transformers may be energised within a minute. An example is illustrated in Fig. 2. Here, the stress on this first transformer is repeated five times (for five step-up transformers) during the total energisation process.

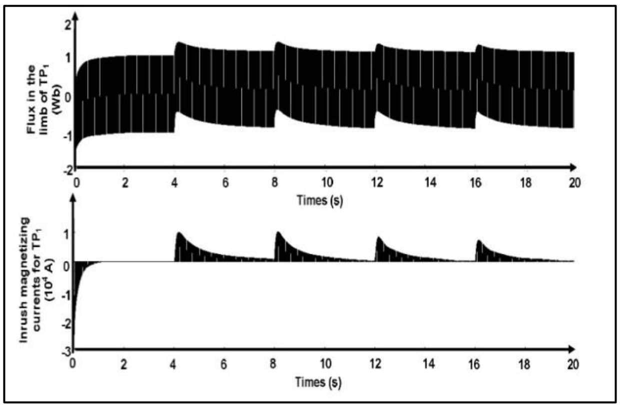

Figure 2 Evolution of the magnetic flux in the iron core and the inrush current of the first transformer [1]

Few literatures discussed about transients in wind farms or discussed further about the effect of inrush such as voltage dips and prolonged mechanical and thermal stresses. Referring to IEC 660076- 16: 2001 Standard [8], frequent wind turbine transformers energisation will bring to mechanical and thermal stresses caused by inrush currents. Same observations were drawn in [9-11]. Also, it should be noted that all these literatures used PSCAD/ EMTDC as the simulation tool in the investigation.

SIMULATION MODELLING

The simulation model is studied using the software tool PSCAD/EMTDC. The distribution networks were modelled in order to observe the output waveforms. Firstly, this part describes the modelling of two transformers in parallel in order to observe the energising inrush current and the corresponding sympathetic inrush.

Secondly, comparisons were made for the case of three parallel-connected transformers: with three transformers connected energised simultaneously, two transformers energised simultaneously with one transformer already in operation, and two transformers energised one by one, with an energised transformer.

Thirdly, the simulations for observing the sympathetic impact from a number of already energised transformers are performed.

Modelling of System under Study

The study started with two three-phase transformers. Transformer ratings are 16 kVA, 11kV/250V. Note that for all the graphs in this subsection, y-axis denotes current in amperes and x-axis denotes time in seconds.

The one-line diagram is shown in Fig. 3. From this circuit, it is expected to see sympathetic inrush occur in T1 during connecting the unloaded T2 to the grid. Fig. 4 shows the magnetising and sympathetic inrush current waveforms with their magnitudes varying in alternate value.

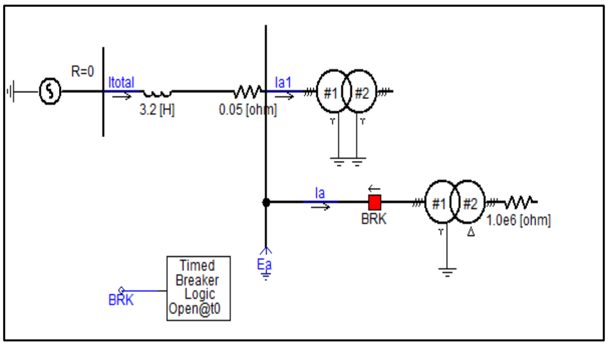

Figure 3 Network under study

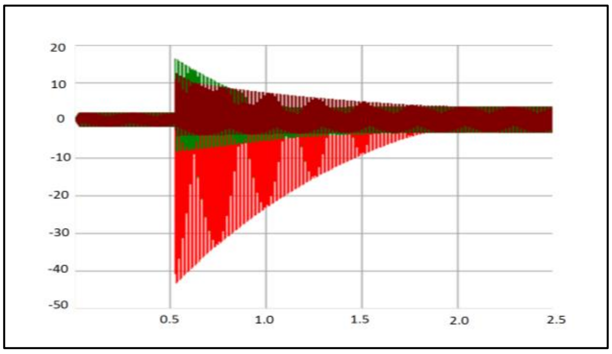

Figure 4 Magnetising and Sympathetic Inrush Currents

Simultaneous Energisation of Several Transformers

A small scaled wind farm is simulated next which consists of 3 same rated 10 kW wind turbines. Each turbine is connected to the 11 kV transformer, rated 16 kVA. Fig. 5 shows the three phase energisation currents when these three transformers are energised simultaneously, with no initially energised transformer. It should be noted that no more than three transformers should be energised simultaneously to ensure compliance with P28c [12].

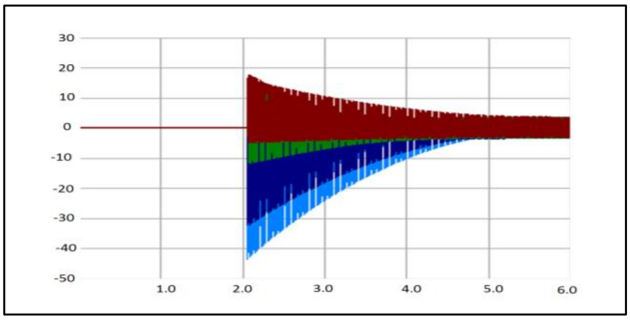

Figure 5 Inrush currents when T1, T2 and T3 energised simultaneously

Subsequently, the simulation is extended to investigate the effect of the inrush current when two transformers are energised simultaneously whilst the first transformer is already in operation. Fig. 6 shows the inrush current waveforms.

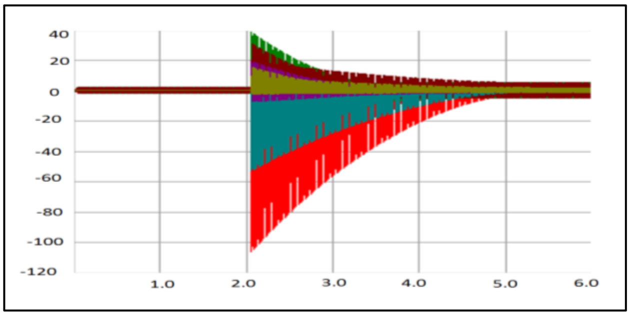

Figure 6 Inrush currents when T2 and T3 energised simultaneously with T1 initially energised

By comparing Fig. 5 and 6, it can be seen that the inrush current is more damped when energising transformers without any initially energised transformer. With the initially energised transformer, it prolongs the decaying time. From Fig. 5, the decay is complete after 5.12 s whereas in Fig. 6, it occurs at 5.20 s.

However, if T2 and T3 are energised at different times, with T1 initially energised; the waveforms are shown in Fig. 7. The peak of sympathetic inrush is higher but the decay time is more or less the same.

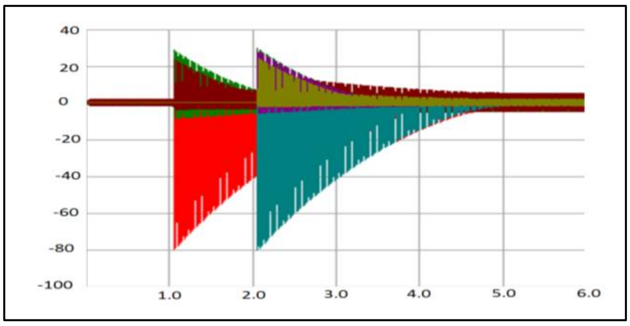

Figure 7 Inrush currents when T2 and T3 energised at different time with T1 initially energised

Inrush Current Impact for Increasing Number of Already Energised Transformers

There are several different possible scenarios of energisation. Simulations were carried out to study the difference from two cases:

a) Case 1: Energise T3 with T1 and T2 already energised
b) Case 2: Energise T2 and T3 with T1 already energised

From both cases, the inrush currents are examined to determine the worst case energisation.

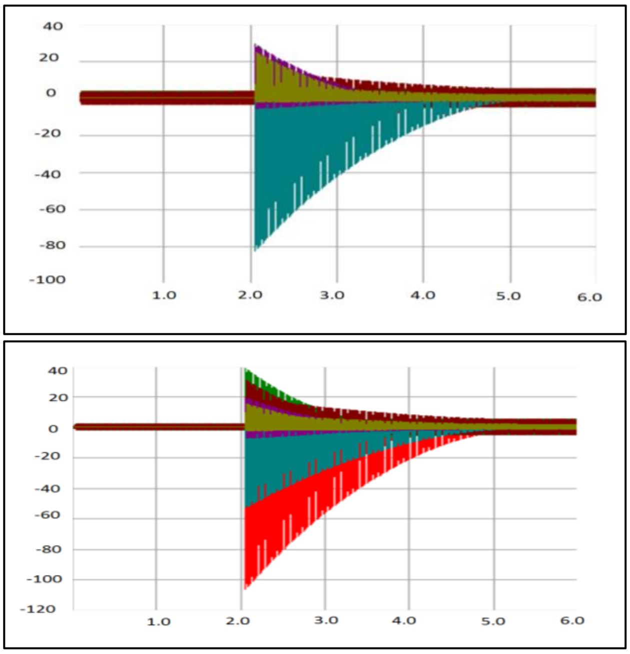

Figure 8 a) Case 1: Energise T3 with T1 and T2 already energised; b) Case 2: Energise T2 and T3 with T1 already energised

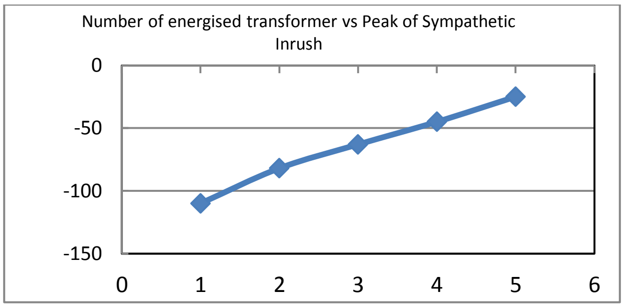

Figure 9 Impacts of numbers of already energised transformer on the peak of sympathetic inrush

By referring to Figure 8 (a) and (b), the peak of sympathetic inrush is -81 A for two already energised transformers whereas it is larger at -112 A for one already energised transformer. Simulation studies were then further carried out to observe the impacts of number of already energised transformers on the peak of sympathetic inrush. Referring to Fig. 9, these simulation studies show that by increasing the number of already energised transformers, the peak of the sympathetic inrush appears to increase proportionally. The duration of the transient inrush is longer as well.

LABORATORY EXPERIMENT VALIDATION

Network Topology

Many previous studies have been carried out to explain the sympathetic inrush phenomenon and its derivation of the mathematical formulations. However, it would be of interest to conduct laboratory experiment to observe this phenomenon. Therefore, a small scale experiment was set up in the laboratory to measure the transients and compare the results to that of simulation.

In the first stage of the experiment, open-circuit test and short-circuit test were performed in order to determine the equivalent circuit of the transformers. Modelling of the transformer is done to obtain the magnetic flux saturation curve.

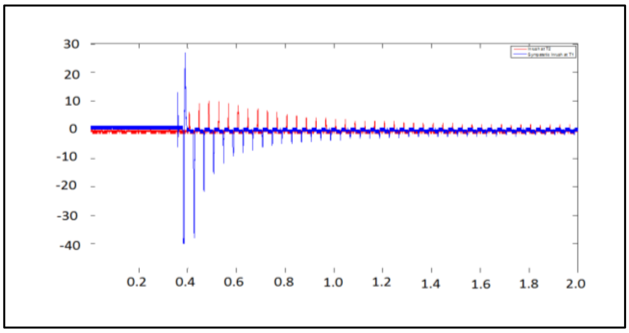

Figure 10 Magnetising and Sympathetic Inrush Current in Energising Parallel-Connected Transformers

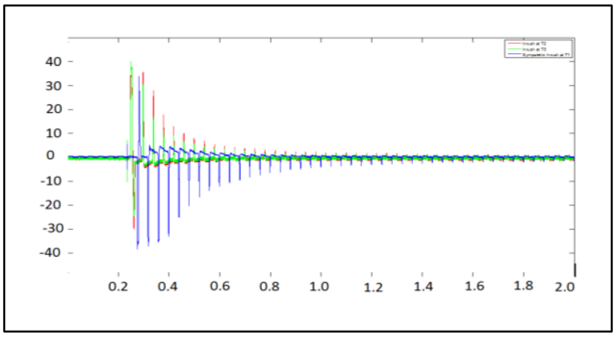

Figure 11 Inrush Current Transients for energising T2 and T3 simultaneously with initially energised T1

Next, two transformers have been set up to observe the inrush transients occur in the system. Fig. 10 shows the sympathetic and magnetising inrush between 2 parallel-connected transformers. The result is very similar to the

PSCAD simulation, thus it validates the transformer model. However, the PSCAD simulation result decays faster as compared to that obtained from the experiment. It may be due to the different damping within the system.

Subsequently, T3 is connected in parallel to T1 and T2. T2 and T3 are simultaneously energised with T1 already in operation. The result is shown in Fig. 11 and it can be observed that the duration of the transient inrush is longer. This verifies the PSCAD model.

CONCLUSION

Through this paper, the energising inrush current transients in parallel-connected transformers are presented; both in simulation modelling and laboratory work. It is observed that:

a) Sympathetic inrush will occur if the other transformers are connected in parallel connection or in the same voltage-level interaction.
b) The inrush current when energising transformers simultaneously is more severe with initially energised transformer connected to it.
c) Increasing the number of already energised transformers will increase the sympathetic inrush current transients.

In general, all the model representations and transient response waveforms show good similarity to those obtained from experiment. Transformer behaviours are confirmed by experiment as well as simulation of sympathetic phenomenon when several transformers are involved. The practical results also support the theoretical predictions.

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