

## New Possibilities in Inrush Current Phenomena Analysis

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Transformers are widely used in power systems and therefore play an important role in energy consumption. Inrush current is magnetizing current which occurs during switching unloaded transformer on to electric grid. Amplitude of this current can be between 3 to 40 times higher than nominal rated current of transformer [1]. Ratio of inrush current amplitude and transformer nominal current is decreased with higher rated power of transformer. During inrush current appearance, complete core saturation can occur [2]. Inrush current waveform is highly non-sinusoidal with large content of higher harmonics [3]. This current can cause many problems, which are explained in [1-5] and will be mentioned later. The problem of inrush current phenomena is known from year 1912, when it was mentioned that during switching of unloaded transformer on grid, a high current is created. During this period, it was not possible yet to determine the amount and waveform of this current, because of non-existence of such measurement systems. Also, reliable analytical calculations were not available. Specht [6], gives one of the first reliable analytical calculations for determining inrush current amount [7]. Holcomb [8], gives improved version of Specht's calculation which can determine inrush current wave form and amount in each cycle, as current decreases with time. Bretangoli [9], gives the simplest equation for fast calculation of inrush current maximal amount. Analytical calculations have precision of  $\pm 40\%$ , which is not good for a reliable estimation. Development of different programs such as DigSilent, ATP, Matlab and LabView enabled more accurate determination of inrush current amount, wave form, harmonic analysis and other influences on inrush current value, which cannot be determined with analytical calculations. These programs have enabled modeling and testing of transformers in purpose of analysis, diagnostics, prediction and prevention of fault stages. In papers [10,11] inrush current analysis is made on distribution transformers, used in power system in ATP and DigSilent program. Analysis are made for case of unloaded transformer random switch with no possibility of changing switch time moment, which has a major influence on inrush current amount. Simple modeling of transformer for different examination stages in Matlab program is given [12]. As new possibility for inrush current phenomena analysis, a new simulation model with possibility of analysis inrush current for different switch times, harmonic analysis of inrush current waveform, different ground connections of transformer and influence of inrush current when transformers work in parallel (mutual effects) will be proposed. For simulation model evaluation, it is necessary to examine simulation results with laboratory measurements and measurements made using protective relays in real power system. For rough estimation of gained results fast analytical methods like [9] could be used. For evaluation using laboratory measurements, it is necessary to have measurement system for transformer inrush current determination [13]. Measurement system has a possibility of higher harmonic analysis, which gives an opportunity to examine gained simulation results for each harmonic member of inrush current. Using field measurements in distribution power system, [14] further evaluation of simulation model could be performed. Field measurements are made by using protection relay REF54x implemented in transformation station 20/0.4 kV. Relay has a possibility of inrush current wave form recording, determination of its amplitude and Fourier analysis of higher harmonics.

### Inrush Current Problems and Solutions

There are many known technical problems, caused by inrush current and they are stated and elaborated in numerous literatures [15-19]. Some of most relevant problems could be stated as follows:

- If transformer is frequently switching, inrush current can cause the isolation brake, because random switching could hit the moment when inrush current has maximal value (this is the moment when switching on occurs in time when phase voltage is equal to zero).
- Even more important problem arises from higher harmonics in inrush current waveform. These harmonics can cause overvoltage and resonance appearances throughout the system, effecting the other transformers and consumers of electrical energy. Effects of higher harmonic influence are given in [18].
- Special problem occurs if large number of transformers is being switched on grid after break in electric energy supply, because of appearance of higher harmonics.
- Higher harmonics in inrush current can cause many problems after switching transformers in industrial facilities (supply voltage 6 kV).
- Mutual effect occurs if transformer is being switched on bus, where other transformers are already switched. Disturbances caused by switched transformer are transferred to other transformers and consumers in the area.

It is important to mention that the inrush current peaks are higher for smaller transformers, but duration of this phenomenon (time necessary for inrush current drop to 50% of its value) is longer for larger transformers. Accurate estimation of second and fifth harmonic is very important, because the protection of transformer depends on amount of these harmonics, which need to be set in protection relays. Mentioned harmonics in modern transformers could have very low amplitude, which cannot be registered by relay protection. Measurements of these harmonics for different transformer switching times will be specially emphasized in proposed simulation model. Techniques for inrush current reduction based on controlled transformer switching are given in [20-24]. These techniques are used on large transformers and because of expensive equipment; they are not used on distribution transformers. Harmonic influence on protective relay system and measures for preventing fault relay operation are given in an overview

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[25]. Some researchers [26-28] deal with recognition of inrush current stage and stage of internal fault in transformer windings. These stages are determined and distinguished with higher harmonic content.

### Proposed Model for Combined Inrush Current Analysis

As mentioned, proposed combined simulation model covers the area of transition behavior analysis of power transformer with the main accent on inrush current analysis for different switching times, different ground connections of transformer and influence of inrush current when power transformers work in parallel state. In parallel state of two or more transformers, mutual effect of one transformer to other is examined as influence of switched transformer on consumers, connected to a transformer in nominal working state. Also, simulation model covers the area of higher harmonic analysis to determine influence of higher harmonics, as a content of some harmonics determines recognition of inrush current phenomena, what is knowledge needed for proper adjustment of protection relays.

A special accent is given in examination of grounding influence on transformer inrush current amount. Cases of direct grounding with various resistance or damping inductance and case of isolated neutral point are examined in detail. Values of grounding resistances is set by using available data which can be found in [29-31], where resistance values are set to limit ground currents to 150 A or 300 A. Also, other values of resistance are examined. It could be concluded that inrush current amount could be significantly decreased by proper choosing of grounding resistance or inductance. Mentioned model is realized by using Matlab program package and part of program called Matlab Simulink, which is used for different kinds of simulations. Also, model provides data input for *B-H* magnetizing curve description. Model consists of: three phase power source, air conduit with data based on  $\Pi$  conduit scheme, three phase breakers, belonging elements for measuring, three phase transformers, algorithm for transformer data calculation and other elements. Examined voltage levels are 10/0.4 kV and 20/0.4 kV and transformer power range from 50 to 4000 kVA. Also, model could be used for testing of different voltage levels and power ranges of transformer.

### Discussion and Conclusion

By revision of available literature, it is determined that recording and analysis of inrush current on large transformers in real network are not performed because of expensive measurement equipment. Used values for determination of inrush current amplitude are gained from analytical methods, which can have determination precision  $\pm 40\%$ . Detailed influence analyses of higher harmonics are not performed on large scale number of power transformers. Examination laboratories mostly do not have possibility of magnetizing curve measuring of power transformers and possibility of direct switching of transformer on nominal voltage value. Furthermore, influences of ground connections on inrush current value as influence of inrush current in parallel state of transformers are not well examined. There is no database with the exact values of inrush current and harmonic analysis of this current for larger number of distribution transformers of different power range, winding connections and ground connections. Mostly, in available literature could be found data from about 2 or 3 tested transformers, without harmonic analysis of inrush current. Special problem presents gathering of essential data and parameters of distribution transformers, so they could be tested in programs in which they are modeled. There is no exact and detailed procedure and measuring equipment which will provide recording of inrush current, in purpose of its amplitude determination and harmonic analysis.

From stated above, new possibility for creation of combined simulation model arises. This model provides detailed examination of inrush current influence on examined transformer, protective relays and consumers. Also, there is a possibility of higher harmonic analysis, ground influence analysis and analysis of influence in parallel state of power transformers.

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