Abstract

This doctoral dissertation focused on designing a proposed controller and implementing the controller in eliminating magnetizing inrush current of transformer. Transformer is the most simple form of ac machine (discovered in early 20th century). It transfers electrical energy from one voltage level to another with isolation. Transformers are widely used in power transmission and distribution system and considered as a key component of the power system. Both steady state performance and by and large the transient performance of the transformer has a significant contribution to power system stable and efficient operation. The transient performance of the transformer mainly affects the overall system operation as well as the life span of the transformer. In practice power transformer switching takes place quite frequently during power system operation. But almost every time it is switched-ON, it gives rise to magnetizing inrush current in the system for initial few cycles. Though it is not classified as a fault, it nevertheless hampers the system stability and performance in various ways. For stable operation, an efficient scheme has to be developed to avoid the case of magnetizing inrush or transient during every switching operations.

Switching transient is mainly dependent upon the magnetic saturation characteristics of the core. The transformer core exhibit considerable non-linearity beyond knee point. This non-linearity is even more prominent in presence of saturation. Under saturation condition, the core draws heavy magnetizing current at the time of energization .

The basis for nullifying the effect of flux asymmetry due to core overfluxing or to restrict the core to enter into saturation is by (a) providing damping resistance, (b) modifying the core design (c) using compensator (d) soft starting (e) controlled switching. In the simplest method a resistor in series is provided to limit the magnitude and the duration of inrush current by reducing the time constant; Some researchers introduce some modification in core design to enhance the flux linking capability of the core. Either air gap is introduced or the distribution of the windings are changed in this scheme. With this adoption in design transformer are less prone to switching inrush as well as peak of

the inrush is restricted. In the compensation method by tracking the first peak of the inrush necessary opposite current is injected in the main power loop through an auxiliary current transformer. Whereas, in soft starting method, initial applied voltage is reduced to achieve inrush-free switching. Lastly under controlled switching, the power-ON instant is controlled in such a way that the core can never attain saturation. Last described method is found to be more effective in the practical point of view.

In this present thesis a controller is proposed and implemented, which controls the switching instant so as such to minimize the core flux ovefluxing and subsequent saturation (originally suggested by Lin et al. [6]). Then it is modified by Brunke et al.[18], [19] in 2001. Here the asymmetrical flux build up in a particular direction (either +ve or -ve) is limited by reducing the mismatching level between the original instantaneous core flux (*i.e.*, remnant) and the applied flux level at the switching instant. So, that initial flux builds up occur in a symmetrical steady state manner and it can never enters into the saturation region. In this thesis a novel scheme is suggested to estimate the residual flux and then how to practically obtain the flux matching criterion at the starting in order to avoid core saturation or over-fluxing. The methods are designed keeping in account of hysteresis, non-linearity and saturation effects of the transformer. The proposed method also take care of the transients due to the other component (like transmission lines, parallel transformer) connected to the systems.

The scheme although reasonably accurate, but is not as simple as the series insertion resistance method. It is compared to be easier than improving core design method or series compensator method. Once the residual flux information is available, next optimum switching instant can be estimated automatically and subsequent re-energization is achieved. It may be pointed out that the main cause of inrush *i.e.*, asymmetrical build up core flux during some initial cycles. So, the estimation of actual flux pattern both at steady state and transient operation is very vital and it ultimately decides the optimal switching instant prediction. The method used by Xu et al. [43], for residual flux prediction by not considering the exact saturation characteristics and again the controlled switching as proposed by them largely depend on circuit breaker statistical time lag operation. Naturally it is prone to miss the exact optimal re-energization instant (as decided by controlled switching algorithm), because circuit breaker operating characteristics are not specific. Delayed switching may avoid this happening with independent pole breaker characteristics. Again delayed switching often leads to rise in breaker voltage at the energization instant and longer duration of single phasing operations. Here these adverse circumstances (probability) are avoided, when actual re-energization is carried out with the help of power electronic switch like triac (solid state switch instead of CB). The scheme is having less switching loss and less turn-on time delay, fast operation. Hardly any chance left there to miss the actual (proper) re-energization instant.

The controller is designed as such to trap any transients associated with transformer operation. It also tracks the switching-ON and OFF transients in an extensive way with all minute details. So, during transition, the changes in the magnetization characteristics or dynamic hysteresis can be well predicted and estimated and finally the value of residual to which the core settles can be calculated with more accuracy and resolution. The every minor details of these studies are documented and illustrated in the later chapters.

Next a theoretical model of the test transformer core is developed, which describes the inter-dependency between electrical and magnetic variable as well as helps to determine the transformer operating characteristics in a interesting and simple way. It also find a functional relationship between electrical and magnetic behavior. This take into account non-linearity due to both hysteresis and saturation characteristics of the ferromagnetic core. Well accepted ferromagnetic model of hysteresis such as Perisach and Jiles*et al*[12] are mainly referred while deriving the non-linear relationship between flux and current. In this consideration, leakage flux through the air path, tank and bolt can be neglected. Leakage flux distribution through primary and secondary winding and core inter winding spaces according to the physical distribution is well assumed during model derivation. After defining the ferromagnetic core model, rest of the electrical circuit representations and governing equations are formulated. Simulation is carried out to indicate or to obtain the unknown electrical and magnetic variables and operating characteristics of the transformer. Cases like steady state, switching transients, saturation region of operation as well as the steady state and the dynamic hysteresis at various operating condition can be adequately simulated. This model is able to determine the steady state and dynamic core flux or remnant of core at arbitrary de-energisation point. Then with a particular value of remnant, next re-energization instant is varied and it is found that, the energization instant flux corresponding the same remnant leads to inrush free switching operation at simulation studies.

The same scheme was modified appropriately to mitigate inrush and transient during energization of three phase transformer. Here also a particular phase remnant out of three is tracked to successfully re-energize all the phases of three phase transformer without any inrush. Basically the overall operation is performed in two steps

- In the first step the recorded remnant of the specific phase is set to match with that of re-energization instant applied flux for optimal re-energization.

- Then in the next step, rest of the two phases are energized, when the dynamic residual flux of these two becomes equal to their respective applied flux. This point generally appears after 4-5 cycles of first phase energization and at the flux peak point of the energized phase. This condition can be tracked and the optimal energization of all the phases can be achieved.

The advantage here is, instead of three steps energization is complete with the help of two steps. Three residual flux sensing units are also not required and there is no rise in breaker voltage during switching.

This proposed controller was designed, fabricated and implemented to minimize the inrush current of both single phase and three phase transformer. In order to bring out the validity and acceptance of the proposed controller and the derived theoretical model of the transformer, extensive and detailed experimental and simulation studies have been carried out for both single phase (of rating 5kVA, 220/220V, 50Hz) and three phase (of rating 5 kVA,400/220V, 50Hz, core type, D/Y transformer) at various operating condition as well as arbitrary switching conditions. Tests are also carried out for both loaded and unloaded cases and for different configurations. Due to non availability of of shell type transformer, the study is restricted to that part. It is interesting to find that experimental and theoretical studies are in excellent agreement. The efficacy of the proposed controller was verified by almost eliminating the undesirable inrush in all cases. Switching-On transients and the associated loss are considerably minimum in this scheme.