Electrical Power and Energy Systems 76 (2016) 156–164

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Mitigation of magnetic inrush current during controlled energization of coupled un-loaded power transformers in presence of residual flux without load side voltage measurements

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ARTICLE INFO

Article history:
Received 9 March 2015
Received in revised form 26 September 2015
Accepted 10 November 2015
Available online 21 November 2015

Keywords:
Controlled energization
Rate of decay of dielectric strength
Residual flux
Inter-phase coupling

ABSTRACT

This paper presents a novel approach for minimizing magnetic inrush current to a level as low as no load current during controlled energization of coupled un-loaded power transformers in presence of residual fluxes without employing load side voltage measurements. The suggested method has been evaluated for power transformers having various winding connections, design configurations (magnetically dependent and independent type), its side of energization (Δ or Y) and different level & polarities of residual fluxes. The effect of breaker performance in terms of variation in dielectric properties and operating time of circuit breakers has also been explored. The method is applied successfully on various 765/400/33 kV power (auto) transformers with delta connected tertiary winding on an existing Indian power transmission network and results, for a couple of cases, are presented. Based on simulation results, it has been observed that the inrush current for a number of transformers has been managed below 5% of its full load current rating. This validates applicability of the proposed technique in real system applications.

Introduction

Power transformers are the most expensive and vital components in electrical power system networks. They are used in a variety of configurations and can be switched ON occasionally (yearly basis) or frequently (daily basis). Persistently, the energization of power transformers at levels of 765 kV and even at 400 kV results in heavy inrush currents. This would impose high thermal stresses on power transformers as well as on circuit breakers used to switch ON the same [1]. The inrush currents contain decaying DC component and harmonics in which second, third and fourth harmonics components are the most predominant ones. The magnitude of inrush current can go up to as high as short circuit level and decay of this inrush current may take hundreds of cycles due to high X/R ratio of the system at EHV& UHV levels [2]. Specifically, in relation to switching at unfavourable instance, energization of transformer creates mechanical stress due to the inrush current (considerably high inrush current values are observed for one in six random energization) and electrical stress due to the steep voltage front on the transformer winding [3,4]. Furthermore, the harmonic content & decaying DC component can cause false operation of protective devices, mechanical damage to the transformer windings from magnetic forces and can also, deteriorate power quality of the system [5].

The controlled switching of HVAC circuit breakers is becoming more and more popular as it reduces thermal & dielectric stresses during switching of shunt capacitors, shunt reactors, transformers, and transmission lines. Apart from many technical benefits, controlled switching also offers considerable economic benefits. It includes enhancement in the performance of circuit breaker (CB), mitigation of switching transient, reduction in maintenance cost, life extension of equipment, and power quality improvement. Hence, this is going to increase the life expectancy of circuit breakers as well as of equipment to be switched ON/OFF [6]. Application of intelligent devices for controlled switching of EHV circuit breakers (CBs) is already available in market. Use of controlled switching to assist retrofitting of old circuit breakers is also becoming popular. This is because of the fact that the pressure built up in old circuit breakers is reduced due to aging effect and will result into reduction of committed operating duties of the circuit breaker [7]. Nevertheless, in past, mitigation of inrush currents for transformers has been achieved using pre-insertion resistors (PIR). This is similar to their application to achieve reduction of over voltages

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http://dx.doi.org/10.1016/j.ijepes.2015.11.008
0142-0615/

during no load energization for long lines. However, controlled switching is being promoted due to added advantage of higher reliability compared to PIR. Furthermore, application of PIR has a limitation on number of consecutive operations due to heat dissipation issues of resistor discs [4,8].

Being very old subject, a huge amount of work has been done by various researchers in context to controlled switching of power transformers to mitigate magnetic inrush currents. The effect of residual flux and way to estimate the same which in turn provides reduction in magnetic inrush current has been discussed by various researchers [5,9,10]. Afterward, Sami et al. [11] discussed the method for estimation of saturation characteristics of power transformers. The effects of uncertainty in operating time of circuit breaker and measurement have also been discussed in [12]. Subsequently, Kahrobaee et al. [13] explored the advantage of controlled switching to mitigate inrush current for generator transformer during back charging through grid and normal plant start-up. Furthermore, CIGRE has presented case studies about the mitigating effect for power transformer and cost benefit analysis in various papers and reports [1,3,4,6,14]. Good amount of work is also done by CIGRE in context to requirements of HVAC circuit breakers, associated controlled switching controller and measuring equipment. Also, target switching instant for various transformer winding connection configurations to achieve minimum inrush levels have been investigated in [15–17].

When comes to practical applicability of power transformers at 400 kV level and above, the desired inrush mitigation effect requires key attention on accurate residual flux estimation, which otherwise would result into high amount of inrush currents. The residual flux estimation/measurement becomes quite challenging and will require special techniques to be implemented. Also, the residual flux estimation demands load side voltage measurement which, in many cases, is not available in conventional substation configurations. This results into energization of power transformers with the controlled energization targets disregarding the residual fluxes. However, this may result into substantial level of inrush current which may vary in the range of 1–1.5 pu or may even go up to 2 pu considering the scatter in circuit breaker characteristics. Furthermore, the configuration of power transformers for transmission levels have Y–Δ configuration or have at-least one Δ winding (tertiary) in case of auto transformers and hence, may involve electrical and/or magnetic coupling (3-limb design). For such cases, the dynamic core fluxes need to be considered along with residual fluxes, making the problem more puzzling [14,17]. Hence, a simplified approach is always appreciated to determine a controlled energization target which takes into account the residual fluxes even though load side voltage measurements are not available.

This paper presents a simple and easily applicable approach to mitigate magnetic inrush based on inrush peaks obtained during first time energization of power transformers in presence of various level and polarity of residual flux in individual phases. More importantly, the suggested approach is capable of estimating residual flux for individual phases with a good level of accuracy without utilizing load side voltage measurement. Hence, the proposed methodology recommends operating time correction required for individual circuit breaker pole such that inrush current is reduced to a low level close to 10% of the full load current. Furthermore, in certain cases, where breaker operating time is highly consistent; the inrush currents can be reduced to the no load current of the transformer, which is typically in the range of 1–2% of the full load current for large power transformers. The suggested method can be used for power/auto transformers having various design and connection configurations including electrically coupled (single phase bank or 5 limb construction type with at-least one delta winding) and/or magnetically coupled (3 limb construction for all connection configurations) [17]. At the end, the effects of change in operating time of circuit breaker and its dielectric characteristic variation on inrush mitigation are also explored.

The suggested approach is successfully applied during commissioning of point on wave (POW)–controlled switching controller for various 765/400 kV auto transformer type interconnecting transformers (ICTs) with Δ connected tertiary winding (33 kV) on an existing Indian power transmission network having diverse magnetic inrush signatures. The results obtained with suggested calculative approach found to be in close conformity with the results obtained using real time data acquisition system (presented in Section "Case studies & real-time implementation results") during commissioning exercise. This validates applicability of suggested approach in practical scenario.

Theoretical background

The magnitude of magnetic inrush in case of transformer depends upon residual flux and decay time constant of the R–L series circuit representing transformer. Various switching strategies have been suggested for mitigation of the inrush based on aforesaid two parameters [1,7].

Switching strategies

Generally, three strategies are recommended for mitigating magnetic inrush in power transformers.

(i) Closing at voltage peak neglecting residual fluxes (minimum decaying component due to R–L circuit) – results into moderate level of inrush current-'Compromise solution'.
(ii) Measurement of the residual flux by integrating load side voltages and carryout closing when residual flux becomes equal to prospective flux.
(iii) Controlled de-energization (lock residual flux value to its lowest possible level during each de-energization) followed by controlled energization of the transformer from same winding side in such a way that residual flux becomes equal to the prospective flux.

Both strategies (ii) and (iii) would provide effective inrush mitigation to a very low level. However, strategy (ii) requires additional voltage measurements on load side. Furthermore, most of the times, voltage measurement on the transformer sides is not available. Hence, strategy (iii) is found to be the most suitable among three suggested techniques considering its simplicity and easy in practical application without additional requirement of any supplementary equipment. However, many times, while utilizing strategy (iii), the inrush current cannot be reduced less than the full load current of transformer even-though minimal level of residual fluxes are achieved with controlled de-energization. This is due to the fact that for modern power transformers,

(i) the no load current is kept to the lowest possible level (to minimize no load losses)
(ii) the knee point voltage is kept very close to rated voltage (approximately 1.2 times) and
(iii) core is designed in such a way to achieve very steep change-over from liner to saturation region on B–H curves [4].

In this paper, a novel method to estimate residual flux level of individual phases without load side voltage measurement is presented. Accordingly, the way to calculate closing time correction required to achieve inrush mitigation to the lowest possible level have been investigated to improve performance of strategy (iii) discussed above. Transformer de-energization leaves the