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Mitigation of Inrush Current in Power Transformer using Prefluxing Technique

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Abstract: Transformer is the most expensive component in power system. So this is very necessary to provide sufficient protection for that component. There are many problems which may occur in transformer like over current, overvoltage etc because of faults which can damage the transformer. Damage in transformer can create a serious problem in transmission or distribution of system. Three phase transformer produces severe starting current which is called inrush current. This inrush current induces harmonics which is high in magnitude and generate at the time of re energisation of transformer and it is 2 to 5 times greater than rated current. This current generates several problems like mal operation of relays, damaging the windings and core of transformers. In this paper a technique to mitigate inrush current in three phase transformer which involves injecting some amount of DC flux in the primary of transformer has been proposed, this process is known as prefluxing. After setting the initial fluxes of the transformer it is energized by conventional controlled switching. To verify the effectiveness of the proposed prefluxing method and to mitigate inrush current for transformer, a MATLAB®/simulation model is designed and developed.

Keywords: Inrush Current, Transformer, Prefluxing, MATLAB®/Simulink

1. INTRODUCTION

Nonlinear properties of circuit elements can be a potential source of abnormalities. Transformer magnetizing inrush current is an example. When a transformer is initially connected to a source of AC voltage, there may be a substantial surge of current through the primary winding called inrush current. This is analogous to the inrush current exhibited by an electric motor that is started up by sudden connection to a power source, although transformer inrush is caused by a different phenomenon.

We know that the rate of change of instantaneous flux in a transformer core is proportional to the instantaneous voltage drop across the primary winding or as stated before, the voltage waveform is the derivative of the flux waveform, and the flux waveform is the integral of the voltage waveform. In a continuously-operating transformer, these two waveforms are phase-shifted by 90º. Since flux (Φ) is proportional to the magneto motive force (mmf) in the core and the mmf is proportional to winding current, the current waveform will be in-phase with the flux waveform, and both will be lagging the voltage waveform by 90º. In an ideal transformer the magnetizing current would rise to approximately twice its normal peak value as well generating the necessary mmf to create this higher-than-normal flux. However, most transformers aren't designed with enough of margin between normal flux peaks and the saturation limits to avoid saturating in a condition like this and so the core will almost certainly saturate during this first half-cycle of voltage. During saturation disproportionate amounts of mmf are needed to generate magnetic flux. This means that winding current which creates the mmf to cause flux in the core will disproportionately rise to a value easily exceeding twice its normal peak. This is the mechanism causing inrush current in a transformer primary winding when connected to an AC voltage source. As the magnitude of the inrush current strongly depends on the exact time that electrical connection to the source is made. If the transformer happens to have some residual magnetism in its core at the moment of connection to the source, the inrush could be even more severe. Because of this transformer over current protection devices are usually of "slow-acting" variety so as to tolerate current surges such as this without opening the circuit.

The inrush phenomenon was known to people from years when the transient behavior of RL circuits was studied. The studies related to magnetic materials, BH curves, saturation, etc. enabled scientists to understand the concept in a better way. **Gaowa Wuyun et. al**. in this paper, introduces the residual flux of transformer ferromagnetic-core which is not random when it enters into Power System without load form last cutting off. Firstly, the relationship between residual fluxes and the last exciting current was discussed, then hysteresis loop was divided into three antisymmetric sections according to reversibility of magnetic domains Methods were proposed to calculate residual flux approximately section by section based on the principle of similar-shape and ferromagnetic characters [1]. Scientists started modeling of inrush current by constructing a low frequency model of transformer. **A.M. Miri, et. al**. Modeled a 100 MVA transformer and obtained inrush current in all the three phases [2]. **Kunal J Patel** discuss the effects of inrush current in transformers they describe the fundamental theory and relevant laws of the transformer and inrush current. A number of factors affecting inrush current are discussed. The inrush current theory and their equation are derived. The effects of inrush current are described in brief. The Matlab Sim-Power system is used for the simulation. The simulation results compared with each other and also data available from actual same size transformer. Finally six solutions to inrush current mitigation techniques with a practical low cost answer are provided [3]. **John H. Brunk ahnd Klaus J. Frohlich** theoretically proposed controlled switching as a method to

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mitigate inrush current in a single phase transformer by making a transformer model considering saturation characteristics of magnetic core and an inevitable residual flux. They also introduced the concept of core flux equalization which means equalization of flux in all the three limbs of transformer core when one of the phases is energized. They calculated the inrush in their model for simultaneous closing, rapid closing and delayed closing of circuit breakers [4]. **Ramsis S. Girgis et. Al.** describe the characteristic of inrush current of present design of power transformers. They says that Accurate calculation of peak and % 2nd harmonic of inrush current is critical to appropriate selection of relay protection of a power transformer. A description is given of a rigorous calculation of magnitude and wave-shape of inrush current as a function of the transformer design parameters as well as parameters of the system to which the transformer is connected [5] **Hongkui Li. et. al.** shown the analysis of three phase power transformer winding forces caused by magnetic inrush and short circuit currents. These forces are compared with the corresponding forces due to short-circuit of the windings. Three-dimensional finite element computation of three-phase power transformer is carried out based on the maximum permissible magnetic inrush current value where its amplitude is the same as the rated short-circuit current. To verify the computation results, they are compared with those obtained using Ansys software simulation [6]. **Salman Kahrobaee et. al.** worked on the investigation and mitigation of inrush current in power transformer during black start of an independent power producer plant, energy and power engineering. They describe that when a transformer is energized by the utility, a typical inrush current could be as high as ten times its rated current. This could cause many problems from mechanical stress on transformer windings to harmonics injection and system protection malfunction. There have been numerous researches focusing on calculation and mitigation of the transformer inrush current. With the development of smart grid, distributed generation from independent power pro-ducers (IPPs) is growing rapidly. They simulate the simulation model in DIgSILENT Power Factory software [7]. **Mukesh Nagpal et. al.** proposed a technique to mitigate inrush current of start transformer by introducing a neutral resistor. They simulated results for both, simultaneous closing and delayed closing of circuit breakers [8]. **Juei Shyu et. al.** proposed a model to reduce inrush current of a single-phase transformer by using voltage series compensation. he used voltage sag caused by switching to control the voltage of a compensator [9]. In [10-17] several worked on sequential energisation of three phase transformers along with a neutral resistor. They made a steady state analysis of transformer with neutral resistor and plotted the inrush peak for its different values. They also formulated optimal neutral resistor for mitigation of inrush current.

2. PROBLEM FORMULATION

The inrush current has already been described in Chapter 1. This inrush current is very harmful for transformers. It can burn the transformer winding due to heating up of winding. When the transformers starts, high magnitude harmonics rich current generated in the transformer, this high current generated due to high flux in air gap in transformers. This high current heating up the winding and the dangerous situation can be created in the transformers [5].

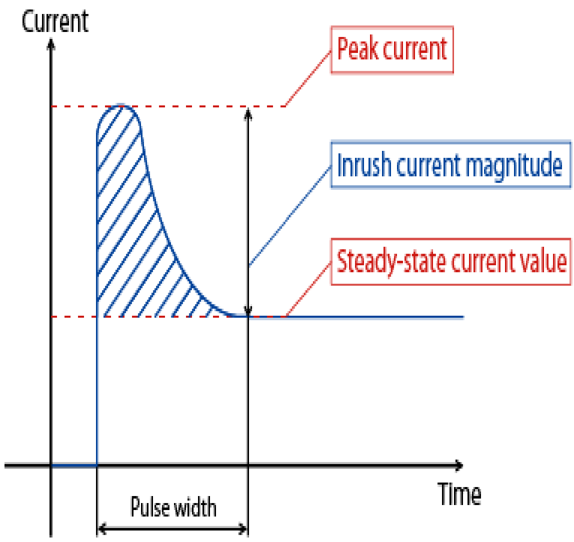

Figure 1: Current waveform

Figure 1 shows a general waveform with inrush current magnitude, peak current and steady state current. At the time of starting of electrical equipment large current get generated in the equipment and it is tries to exceed the peak current. The main reason to generate the inrush current is flux. When a electrical equipment is de energized, some flux remain in the core or air gap of the equipment and when again energized the same equipment, the flux trying to reach beyond the maximum value of $2\Phi_{max}$, it becomes constant but current is always proportional to flux so the current increased gradually and reaches 5 to 10 times greater than full load current of equipment [6]. When transformer energized, several currents flows in transformer which are shown in figure 2. Current 1 is peak current, current 2 is large pulse width current and current 3 is mal functioning current. Peak current is the current which is maximum value of current either positive or negative direction of the transformer. Large pulse width current has large value of width in each steps of sinusoidal wave. Mal function current is generated by inrush phenomena. It can also call as false function current.

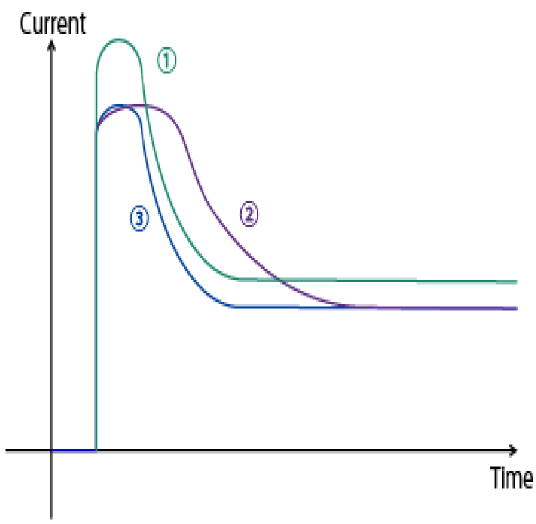

Figure 2: Inrush current waveforms [6]

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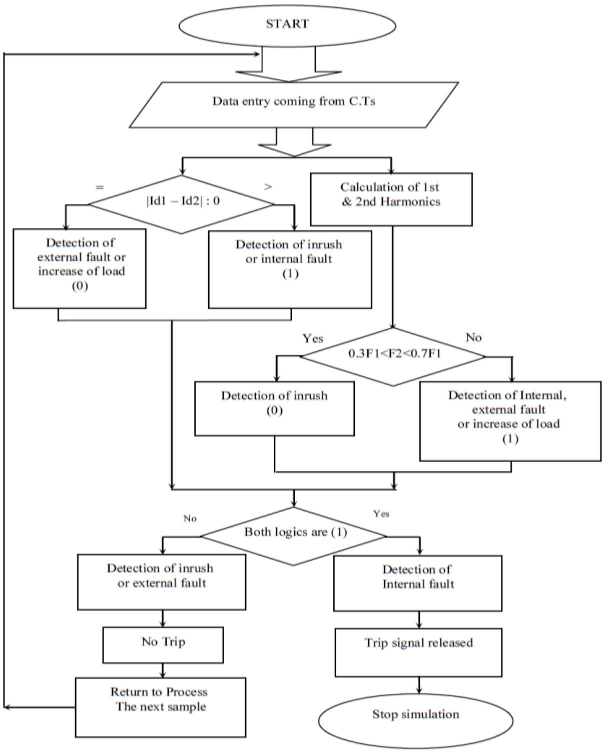

Figure 3: Flow chart to differentiate the inrush current

Figure 3 shown the flow chart of differentiate inrush current. As the transformer re energized, current will flow in the primary core of transformer. The value of current (magnitude and phase) is measured by current transformer , which discriminate between normal current and fault current. In next step, preset value compare the current with calculated value and 1st and 2nd harmonics are also calculated in the calculated current. If 1st and 2nd harmonics are present with large value in the current, it shows that inrush current is present and if both harmonics absent which means there are internal or external faults are present in the transformer. Both, the magnitude and presence of harmonics are decide about the next step to protect the transformer. If there is inrush current or external fault present, the transformer do not trip but if there is internal fault present, the transformer will trip immediately. For the next samples, this process repeat again and again.

3. REDUCTION TECHNIQUES

There are many methods to mitigate inrush current like injection of resistor in system, injection of voltage by Pulse Width Modulation, Point on Wave switching (POW). This Chapter describes a new method to mitigate inrush current which called prefluxing and modeling to mitigate inrush current with using prefluxing. A filter is also used in prefluxing device to control the harmonics in power transformer. The prefluxing technique is the combination of POW prefluxing device and filters. In recent years, various protection systems for transformers based on the differential relaying were developed. Various techniques based on complex circuit or microcomputers are proposed to distinguish inrush current fault current. However, the transformer still must bear with large electromagnetic stress impact caused but the inrush current. The main factors affecting the magnetizing inrush current are POW voltage at the instant of energization, magnitude and polarity of residual flux. Total resistance of the primary winding, power source inductance, air core inductance between the energizing winding and the core, geometry of the transformer core and the maximum flux carrying capability of the core material. From past years many techniques have used to mitigate inrush current for example point on wave switching, pre insertion of resistance in primary of transformer, injection of voltage in tertiary winding etc.

4. MITIGATION OF INRUSH CURRENT IN THREE PHASE POWER TRANSFORMER USING PREFLUXING

A MATLAB Simulink model has prepared for simulation study. Here three phase power transformers having a rating of 250 MVA, 11/400 KV, 50 Hz, connected to a supply source as shown in Figure 4. This model used prefluxing technique to mitigate inrush current and harmonics. Current and flux measurement devices are connected whose results are also shown in next section. The core is used with specific initial fluxes and saturation limit. Some amount of flux provides in each phase to get the value of inrush current. When the power transformer energized, the flux of all three phases will increase and reach till the maximum value of flux. And after that maximum value of flux will become saturated and drawn more inrush current from source, which may be 5 to 10 time greater than rated current. The main reason of saturation of flux is due to residual. Residual flux is nothing but it is some amount of flux which remains in the core at the time of de energisation of transformer. Residual flux is depending on the rating of power transformer and at the instant on which transformer is deenergizing. It will have different value for different rating transformer. MATLAB Simulink model shown in figure.

5. SIMULATION RESULTS

Prefluxing technique is used to reduce the effect of inrush current and harmonics till 99%. The prefluxing technique discussed in Chapter 4 and the result of transformer after using prefluxing is shown under:

Mitigated Current: Figure shows the current after using prefluxing technique on transformer. The inrush current goes down 99 % by this technique.

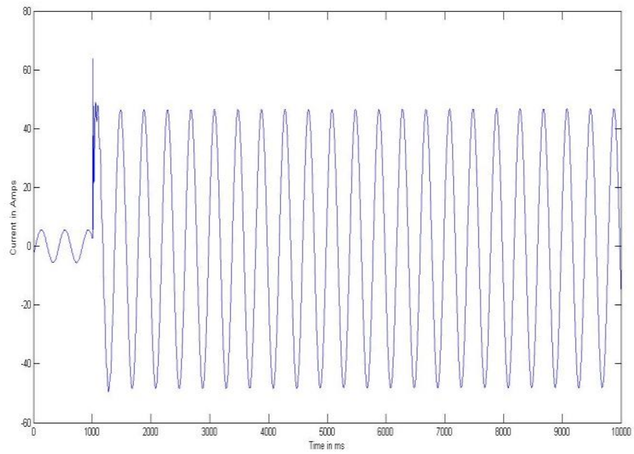

Figure 5 (A) Mitigated current in phase A.

Figure 5 (A) shows the mitigated current in phase A. the magnitude of current is 46 Amp which is normal for transformer while without using any technique the current in phase A was 1700 Amp.

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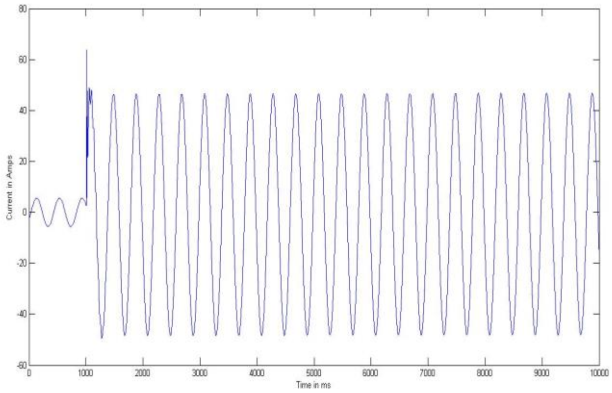

Figure 5 (B) Mitigated current in phase B

Figure 5(B) shows the mitigated current in phase B the magnitude of current is 47 Amp This is normal for transformer while without using any technique, the current in phase B was 1425 Amp.

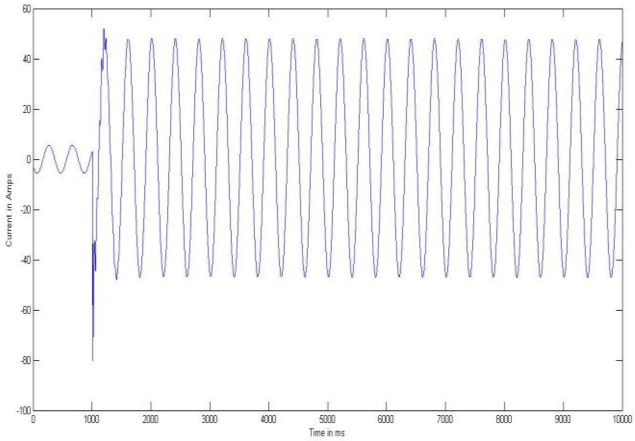

Figure 5 (C) Mitigated current in phase C

Figure 5.(C) shows the mitigated current in phase C the magnitude of current is 46 Amp This is normal for transformer while without using any technique the current in phase C was 410 Amp.

Flux: Flux of all three phases shown in figure 5 (D) This flux is unsaturated flux.

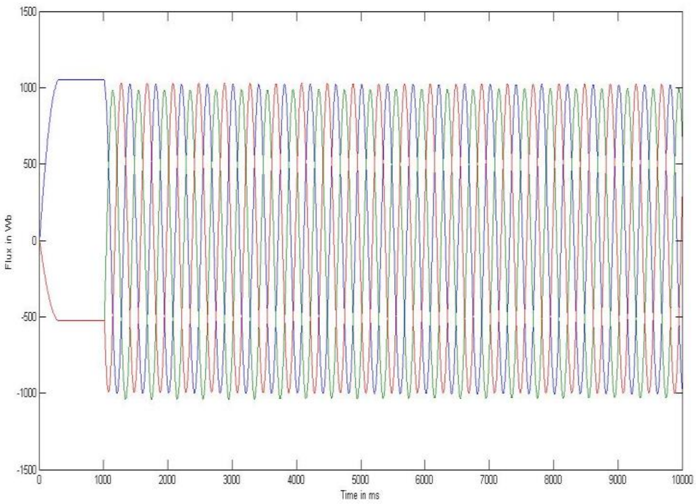

Figure 5 (D) Flux of compensated system

Harmonics: By using prefluxing technique and filter, the harmonics eliminate from the system. Figure 5 (E) shows the harmonics in phase A, phase B and phase C.

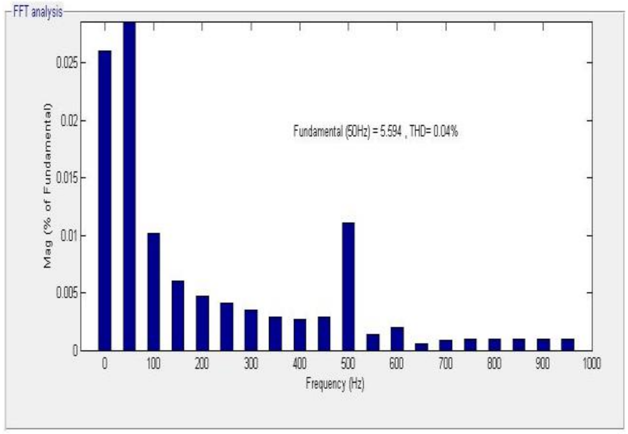

Figure 5 (E1) Harmonics in phase A

Figure 5 (E1) shows the harmonic in phase A. Total harmonic distortion (THD) in phase A is 0.04 %, while THD without using prefluxing is 25.78%. So this technique reduces harmonics 99 %. Fundamental component as figure 5.5 is 0.07 and second harmonic is 0.028

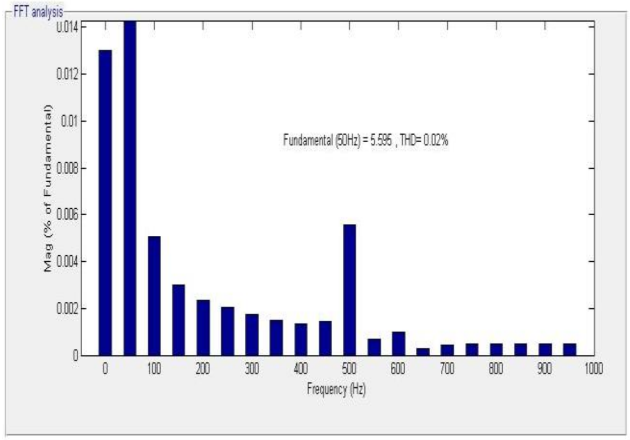

Figure 5(E2) Harmonics in phase B

Figure 5(E2) shows the harmonic in phase B. Total harmonic distortion (THD) in phase B is 0.02 % while THD without using prefluxing is 39.12 %. So this technique reduces harmonics 99 %. Fundamental component as figure 5.6 is 0.0012 and second harmonic is 0.014.

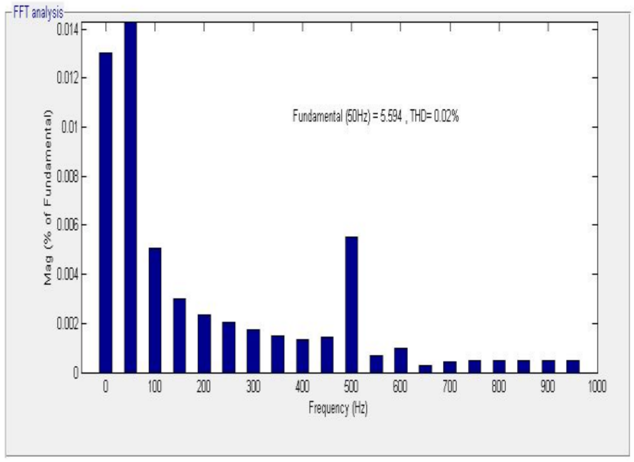

Figure 5 (E3) Harmonics in phase C

Figure 5(E3) shows the harmonic in phase B. Total harmonic distortion (THD) in phase B is 0.02 % while THD without using prefluxing is 81.38 %. So this technique reduces harmonics 99 %. Fundamental component as figure 5.7 is 0.0016 and second harmonic is 0.013.

Table 5.1 Comparison between SSSC and prefluxing technique to mitigate inrush current

Phases	Without using any mitigation technique		Using SSSC		Using prefluxing technique	
	Current	Harmonic	Current	Harmonic	Current	Harmonic
A	1900	25.78	190	17.26	46	0.04
B	1425	39.12	58	28.60	47	0.02
C	410	81.38	60	22.67	46	0.02

As shown by table 5.1, prefluxing technique is far better than SSSC. Prefluxing technique not only mitigates inrush current in transformer but also it eliminates harmonics. SSSC technique can mitigates only 80 percent of inrush current while prefluxing mitigates 98 percent of inrush and harmonics. As shown in above table, there is 1900 Amps of inrush current in phase A which is mitigated by SSSC till 190 Amps while prefluxing mitigated same current till 46 Amps which is almost negligible. The same case can be shown in another two phases, phase B has 1425 Amps current which mitigated 58 Amps by SSSC and 47 Amps by prefluxing and in phase C, generated 410 Amps current which is mitigated till 60 Amps by SSSC and 46 Amps by prefluxing. So the conclusion is that, prefluxing technique is not only economic but also it is very efficient for covering the purpose completely.

6. CONCLUSION

The main purpose of this thesis is to mitigate the inrush current and harmonics which is generated in three phase power transformer. This inrush current is very harmful for transformer. The effect and factors of inrush current on power transformer is also described in this thesis. In this thesis, we have investigate inrush current, harmonics, voltage and flux by using MATLAB®/simulink model and find the high magnitude starting current and total harmonics distortion in transformer .

In this thesis, we have introduce a new technology to reduce the inrush current and harmonics that is called prefluxing technology. This prefluxing is a device which is made by charged capacitor and converter. There are many methods to reduce high starting current and harmonics but all methods reduce only 70% to 80 % starting current and harmonics but in this research, we have reduce 95 % of starting current and harmonics.

7. FUTURE SCOPE

The proposed prefluxing device can replace filter popularly used for harmonics mitigation. It reduces the cost of the system satisfactory extent. This prefluxing device is cheaper in comparison to power electronics compensation devices like SSSC, DVR, UPFC etc to improve stability of system.

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