

Reduction of Three-Phase Transformer Inrush Currents Using Controlled Switching

Joydeep Mitra, *Fellow, IEEE*, Xufeng Xu, and Mohammed Benidris, *Member, IEEE*

Abstract—This paper proposes a new approach for reducing inrush currents in three-phase-three-legged stacked core power transformers. Although magnitudes of inrush currents may not be as high as short circuit currents, they are extremely detrimental to normal operation of power transformers. In this paper, a new controlled switching scheme that takes into consideration both core saturation and residual flux is proposed to reduce inrush currents. Also, a transient model based on the duality transformation between electric and magnetic circuits is proposed where a non-linear inductance is used to simulate core saturation. The proposed scheme is demonstrated on a real transformer by both laboratory experiments and performing simulations. The alternative transients program (ATP) is used to simulate a wide spectrum of possible operating conditions. The experimental and simulation results show that inrush currents are significantly reduced after utilizing the proposed scheme. Therefore, the proposed controlled switching scheme will result in relaxing inrush current related constraints in designing and manufacturing three-phase power transformers which in turn will reduce their cost.

Index Terms—ATP, duality theory, controlled switching, three-phase three-legged core transformer, transient model.

I. INTRODUCTION

POWER transformers play important roles in power transmission and their operating characteristics have significant impacts on power quality and lifetime of power system apparatus. The magnetic current caused by switching transformers without load or recovery from an external fault with sudden voltage rise is defined as inrush current; its peak value can reach ten times the rated current of transformer. This drives the core into saturation, resulting in high harmonic content. The initial inrush often decays quite rapidly, typically in 4–6 cycles, but depending on system conditions it may last several seconds [1]–[3]. Inrush currents cause several detrimental effects on transformers, power system operation, and equipment such as: 1) damage to the transformer itself, due both to the high currents and the resulting mechanical stresses; 2) malfunction of transformer differential protection as well as other protective relays and fuses; 3) power quality issues due to high harmonic content of inrush currents; 4) other system effects, such as system overvoltages, sympathetic inrush in other transformers, and effects on communication systems [3]. Therefore, developing methods or tools to mitigate, prevent,

reduce, or even eliminate inrush currents will increase the lifetime of transformers and other equipment, improve power system operation, and reduce costs related to inrush currents in the manufacturing phase.

Methods to mitigate, prevent, and reduce inrush currents have been under development since the invention of power transformers. The literature on transformer inrush currents can be divided into the following categories: analysis of inrush currents [4]–[6], methods to calculate inrush currents [7]–[11], methods to detect and discriminate inrush currents [12], [13], studying the effects of inrush currents on power system operation and equipment lifetime [14]–[18], investigation of several approaches on practical transformers [19], [20], and modeling of inrush currents [21]–[27].

It is difficult to completely eliminate inrush currents in three-phase transformers. Several methods have been proposed to reduce inrush currents and/or mitigate their effects, either by controlled switching or by design of core and windings [1], [2], [21], [28]–[45]. The work presented in [28] used a grounding resistor connected at the transformer neutral and delayed energization of each phase of the transformer to mitigate inrush currents. An approach based on increasing the transient inductance of the primary coil by changing the distribution of the coil winding has been proposed in [29]. Controlled transformer switching methods based on optimal closing instants for each phase to reduce inrush currents have been proposed in [1], [2]; however, these methods were developed for triplex transformers, i.e., with the three phases wound on separate cores, where there is no magnetic coupling between different phases. In [3], there is a discussion of applying controlled switching to three-legged transformers, with a recommendation to switch phase A at peak voltage and phases B and C a quarter cycle later.

Several electromagnetic transient models have been proposed to study transformer inrush currents. These models can be divided into two categories: magnetic circuit models [9], [20], [46], [47] and equivalent electric circuit models [48]–[50]. For example, authors of [48] have presented a topology-based and duality-derived three-phase, three-winding, core-type transformer model that integrates the leakage inductance and core coupling effects. Also, a magnetizing inrush current model has been developed in [48] from transformer structural parameters. Authors of [49], [50] have developed topologically correct hybrid transformer models for frequencies up to 3–5 kHz. These models utilize duality-based lumped-parameter saturable cores, matrix descriptions of leakage and capacitive effects, and frequency-dependent coil resistances.

Several software packages have been utilized in modeling inrush currents in power transformers including electromag-

Joydeep Mitra is with the Department of Electrical & Computer Engineering, Michigan State University, East Lansing, MI, 48823 USA; e-mail: mitraj@msu.edu.

Xufeng Xu is with the American Electric Power (AEP), New Albany, Ohio 43054 USA; Email: xxu@aep.com.

Mohammed Benidris is with the Department of Electrical & Biomedical Engineering, University of Nevada, Reno, Reno, NV, 89557 USA; e-mail: mbenidris@unr.edu.

netic transients program (EMTP) [30], [46], [49], [50], power system computer aided design (PSCAD) [28], [51], [52], and MATLAB/SIMULINK [53], [54].

This paper proposes a controlled switching scheme for reducing inrush currents in three-phase power transformers that are constructed on a single core. Prior methods, such as [1], [2] were developed for triplex transformers, i.e., banks of single phase transformers connected in three phase, thereby ignoring the magnetic couplings between different phases that occurs in common-core transformers. Although [3] proposed a method for three-legged transformers, its recommendation was to switch phase A at peak voltage and phases B and C a quarter cycle later. Our proposed scheme extends the theory proposed in [1] and [55] and is applied on three-phase three-legged stacked core transformer, and considers the magnetic couplings between the three phases. Unlike in [3], our method determines distinct switching instants that depend upon the transformer parameters and are therefore specific to each transformer. The proposed scheme considers both core saturation and residual flux to reduce inrush currents from the standpoint of optimal epoch angle. Also, a transient model is proposed for simulations and future developments. The proposed model is established based on the duality transformation between electric and magnetic circuits where a non-linear inductance is used to simulate core saturation. The proposed controlled switching scheme is simulated on the ATP (alternative transients program) [56] using the proposed transient model and parameters of a real transformer. Simulated results are validated experimentally on the same real transformer. The proposed switching scheme not only enhances transformer performance but also mitigates the operational and longevity issues associated with inrush.

The remainder of the paper is organized as follows. Section II presents the transient model of three-phase three-legged core power transformers. Section III describes the proposed switching strategy to reduce inrush currents. Section IV presents and discusses the experimental and simulation results. Section V provides concluding remarks.

II. TRANSIENT MODEL OF THREE-LEGGED STACKED CORE TRANSFORMERS

Due to the saturation of core flux, a large current will be generated when energizing a transformer which is called inrush current. One of the methods to reduce inrush currents is controlled switching which requires complete considerations of electromagnetic interactions. However, the mutual coupling between different phases of three-phase stacked core transformer makes it difficult to directly simulate magnetic circuits of transformers. This section presents the proposed method to model a three-phase stacked core transformer and simulate inrush currents.

A. Inrush Current

Ferromagnetic materials of transformers have nonlinear excitation characteristics which are the main cause of inrush currents; a typical magnetization curve and inrush current waveforms are shown in Fig. 1. Power transformers are usually

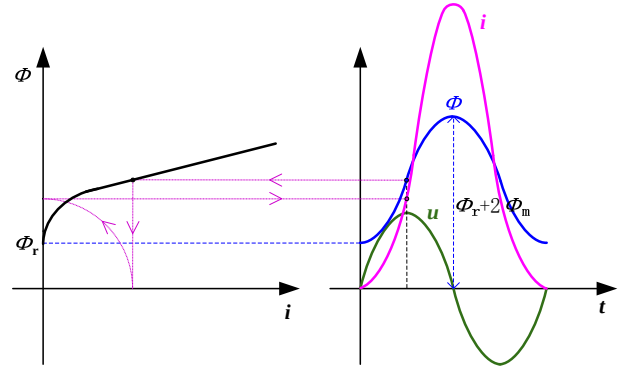


Fig. 1. Magnetization curve and inrush current waveform.

operated with peak core flux which occurs at the knee of the transformer core's saturation curve [1]. Inrush current, i_{inr} , will be small if the magnetic flux, ϕ , is below the saturation flux. However, it increases significantly as ϕ passes the knee point. The inrush current reaches the highest value when ϕ equals to $\phi_r + 2\phi_m$, where ϕ_r is the residual flux and ϕ_m is the maximum mutual flux.

For example, consider energizing a single phase transformer without a load. For this case, the electromotive force (e.m.f.) equation at the primary windings can be expressed as follows.

$$N \frac{d\phi}{dt} + iR = U_m \sin(\omega t + \alpha), \quad (1)$$

where N is the number of winding turns; $N\phi$ is magnetic flux linkage; i is the electric current; R is the resistance of the primary windings; U_m is the maximum induced e.m.f. ($U_m = N\omega\phi_m$); ω is the power frequency; and α is epoch angle of the voltage at switching point.

By solving (1), the magnetic flux, ϕ , at the iron core can be expressed as follows.

$$\phi = \frac{-LU_m \cos(\omega t + \alpha)}{\sqrt{R^2 + (\omega L)^2}} + \left(\phi_r + \frac{LU_m \cos \alpha}{\sqrt{R^2 + (\omega L)^2}} \right) e^{-\frac{R}{L}t}, \quad (2)$$

where L is the inductance of the primary windings. The magnetic flux in (2) is comprised of two components, a steady periodic component and a transient component that decreases exponentially with a time constant of R/L .

According to (2), there are four main factors influencing the decrease of ϕ as follows: (1) the resistance of the primary windings, R ; (2) the inductance of the primary windings, L ; (3) the residual flux, ϕ_r ; and (4) the epoch angle, α . However, it is easier to control α than other factors. The work presented in this paper is based on finding the optimal switching instants for each phase (epoch angles).

B. The Transient Model

According to the magnetic flux distribution of three-phases three-legged stacked core transformers, their equivalent magnetic circuit can be viewed as shown in Fig. 2. The symbols in Fig. 2 are defined as follows: R_a , R_b and R_c represent the magnetic reluctances of the three legs, R_{00} represents the zero sequence flux of each phase, R_{01} and R_{02} represent the leakage flux of the primary and secondary windings

respectively, R_y represents the four yokes of the transformer, and F_H and F_L are the magnetomotive force of the primary and secondary windings respectively.

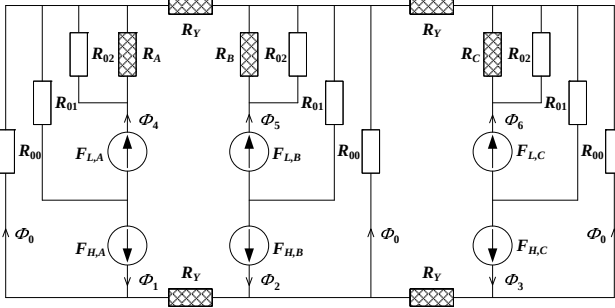


Fig. 2. The equivalent magnetic circuit of a three-phase three-legged stacked core transformer.

Using Kirchhoff's Law of magnetic circuits, we can establish the following equations for phase A (equations for phases B and C can be generated in the same manner).

$$\begin{cases} R_{01}\phi_1 + (R_{01} + R'_A)\phi_4 - F_{L,A} = 0 \\ R_{00}\phi_0 + R_{01}\phi_1 + R_{01}\phi_4 - F_{H,A} = 0 \\ (2R_y - R_{00})\phi_0 - 2R_y\phi_1 + R'_A\phi_4 + F_{H,A} - F_{L,A} = 0 \end{cases} \quad (3)$$

where R'_A equals to $R_A R_{02} / (R_A + R_{02})$ and ϕ_i (where $i = 0, 1, \dots, 6$) are the magnetic flux at different branches as shown in Fig. 2.

Based on the magnetic circuit equations and the configuration of Fig. 2, the mathematical model of the equivalent electrical circuit can be obtained by applying the duality transformation given in [57]. The resulting model is shown in Fig. 3. This model is used to analyze electromagnetic relations of the transformer used in this work, and test the proposed switching strategy.

The symbols shown in Fig. 3 are defined as follows: R_H and R_X are the resistances of the primary and secondary windings respectively, R_1 and L_1 represent the resistance and non-linear inductance of the saturable core limb in each phase respectively, the resistor, R_4 , and the non-linear inductance, X_4 , are used to model the zero flux sequence fluxes, R_y and L_y represent the yoke sections between phases, and X_3 represents the flux leakage.

These parameters can be estimated using the approach given in [50]. R_H , R_X , and X_3 are determined by short circuit tests, R_1 , L_1 , R_y , and L_y are determined by open circuit tests, and R_4 and X_4 are determined by zero sequence tests.

III. THE PROPOSED SWITCHING STRATEGY

To eliminate inrush currents in three phase transformers, Brunke and Frohlich [1], [2] have proposed a controlled schedule of transformer switching. The controlled schedule was determined based on the basic principle that the induced flux at the instant of energization must equal the dynamic flux. However, the developments in [1], [2] are based on triplex transformers which ignore mutual couplings between different

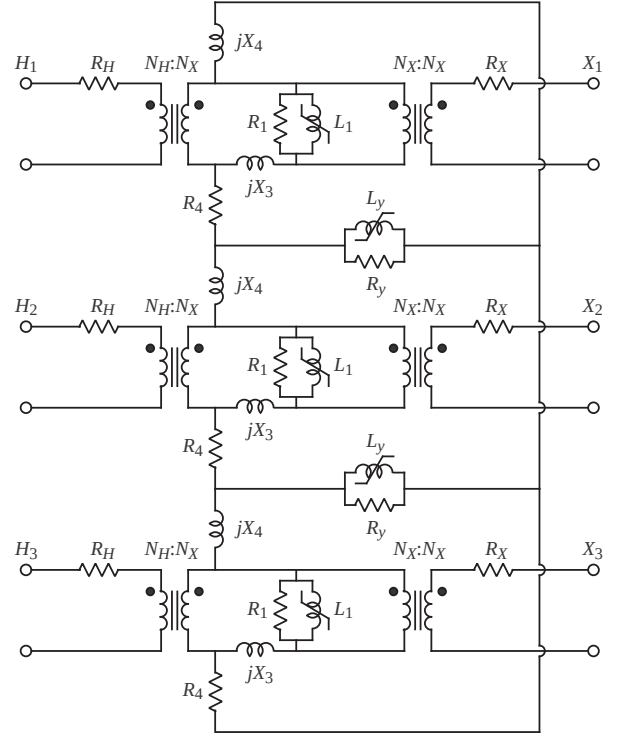


Fig. 3. The equivalent electrical circuit of a three-phase three-legged stacked core transformer.

phases. This paper extends the work presented in [1] to three-phase three-legged stacked core power transformers which are more common in practical power industry than triplex transformers.

As mentioned in [1], the optimal instant to energize a single-phase transformer is when prospective flux is equal to dynamic flux. This principle can also be applied in three-phase transformers since these fluxes are responsible for the inrush current. If residual fluxes in the three phases are assumed to be zero, the optimal instant to close phase A is when the voltage is at the peak value. However, this instant is not an optimum instant for the other two phases because their corresponding fluxes are not zero. The prospective flux waveforms of a three-phase three-legged stacked core transformer are shown in Fig. 4. Because the magnetic flux cannot change immediately, the flux waveforms of all three phases start from zero. The flux waveform of phase A is sinusoidal and it does not contain a transient component. The other two phases are not pure sinusoidal waveforms and contain transient components. This behavior is captured by the second part of (2), i.e., the transient component, which is not zero during transients; transient fluxes will die out after a few cycles.

When phase A is energized, the fluxes in the other two phases will change accordingly as shown in Fig. 5. The magnetic fluxes at the three phases (namely ϕ_A , ϕ_B and ϕ_C) should satisfy the following relationship:

$$\phi_A + \phi_B + \phi_C = 0 \quad (4)$$

Furthermore, the resulting fluxes in the other two phases are not evenly distributed. The magnetic path of phase B is shorter than that of phase C (i.e., $|\phi_B| > \frac{1}{2}\phi_A$ and $|\phi_C| < \frac{1}{2}\phi_A$) as

illustrated in Fig. 5. The optimal instant to energize phase B is also when the magnetic flux of phase B in Fig. 5 equals the prospective flux in Fig. 4.

After phases A and B are energized, the resulting flux waveforms of the three phases are shown in Fig. 6. The resulting dynamic flux in phase C is compared with the prospective flux to determine the instant for energizing phase C.

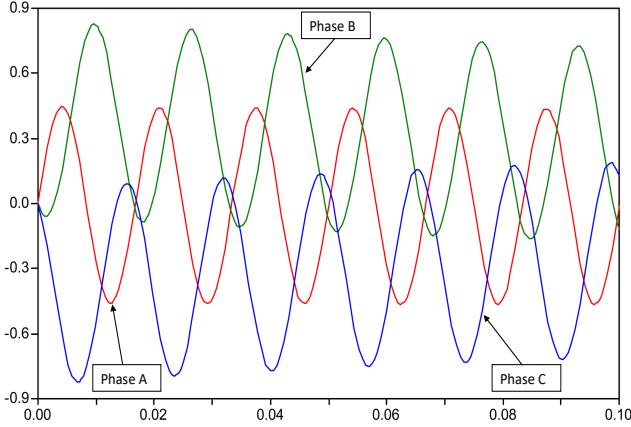


Fig. 4. The prospective flux waveforms of the three phases.

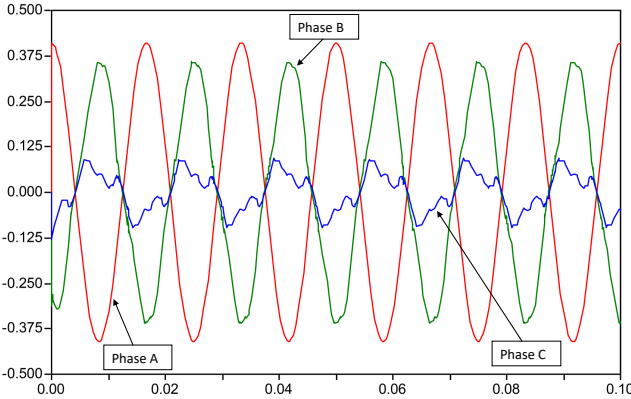


Fig. 5. The dynamic flux waveforms of the three phases after phase A is energized.

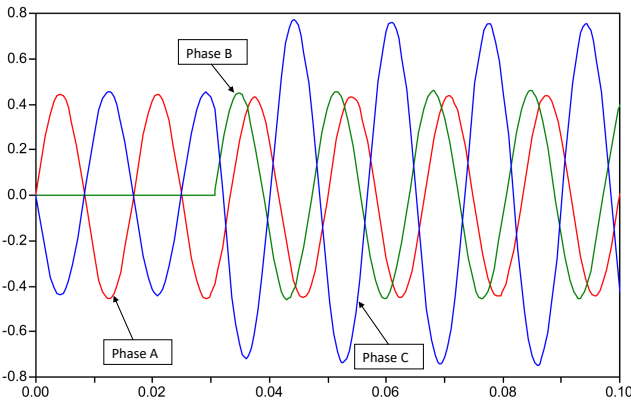


Fig. 6. The dynamic flux waveforms of the three phases after phases A and B are energized.

In the presence of residual fluxes in three-phase three-legged stacked core transformers, the proposed switching strategy is adjusted as follows to ensure it is still effective. First, energize phase A at its optimal switching time as before but energize phases B and C at their optimal switching instants with a delay of two cycles. This is effective because of the phenomenon of core flux equalization [1], which can be understood as follows. When one phase is energized at the optimal switching time (peak voltage and therefore zero prospective flux), the resultant dynamic core flux in other phases will not distribute evenly: they will be at different points of their respective hysteresis loops. As they trace the paths of their respective hysteresis loops one phase will reach the saturation point earlier than the other, and they have different slopes at this instant. Since the slope of hysteresis curve is B/H , one phase will have a higher flux density than the other, and since flux density is directly proportional to voltage, the phase with higher flux density will have a higher voltage. This higher voltage will create a higher flux level which will drive the phase with lower value flux density to higher value and ultimately the fluxes of both phases equalize, thereby negating the effect of their residual fluxes.

The proposed method can now be summarized as follows.

- 1) Determine the transformer parameters and equivalent circuit.
- 2) Simulate the prospective flux waveforms of the three phases.
- 3) Set τ_A as the instant when phase A voltage peaks. Simulate the dynamic flux waveforms, switching phase A at τ_A .
- 4) Compare the phase B waveforms from steps 2 and 3 to determine τ_B , the earliest instant when the phase B dynamic flux equals the phase B prospective flux. Simulate the dynamic flux waveforms again, switching phase A at τ_A and phase B at τ_B .
- 5) Compare the phase C waveforms from steps 2 and 4 to determine τ_C , the earliest instant when the phase C dynamic flux equals the phase C prospective flux.
- 6) τ_A , τ_B and τ_C are the instants when the three phases should be energized, assuming no residual flux. In the more likely case that residual flux is present, delay τ_B and τ_C by two cycles.

The tests and models necessary for step 1 are described in [50]. The background of these models are described in [49].

IV. CASE STUDIES

Simulations and experimental verification are carried out on a three-phase three-legged stacked-core power transformer. This transformer is a dry type unit rated at 15 kVA, Y- Δ connection with voltage ratios of 208Y/240 Δ which is shown in Fig. 7. Transformer parameters are measured using the method mentioned in section II and their values are given in Table I.

A. Simulations

The ATP software is used to perform the simulations. The transient model of section II is used for demonstrating the proposed switching strategy. The ATP model is shown in Fig.



Fig. 7. Three phase transformer used in these experiments.

 TABLE I
MEASURED TRANSFORMER PARAMETERS

Phase	R_H	R_4	X_4	X_3	R_1	R_X	R_y
A	0.1754	0.2112	0.3703	0.0267	412.88	0.0393	312.74
B	0.1786	0.2112	0.3703	0.0273	412.88	0.0389	312.74
C	0.1771	0.2112	0.3703	0.0277	412.88	0.0389	312.74

8. To prevent a floating sub-network, a resistor, R_2 , with the value of 10^{-6} is added. Also, to model the neutral wire, a resistor, R_3 , with the value of 10^5 is added.

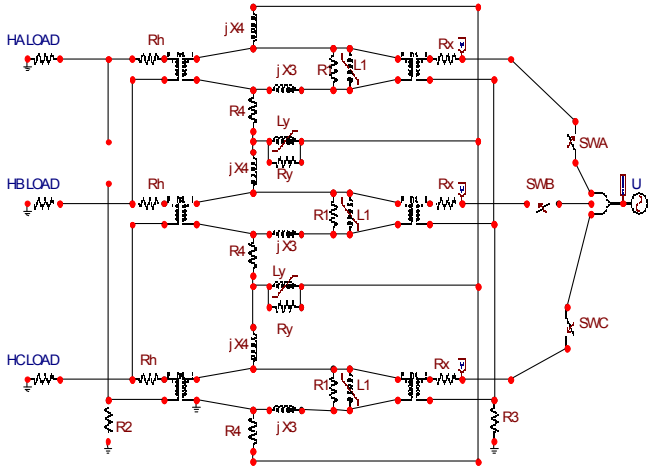
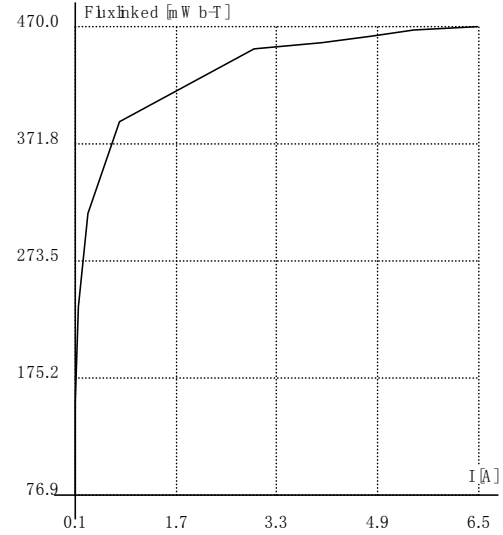
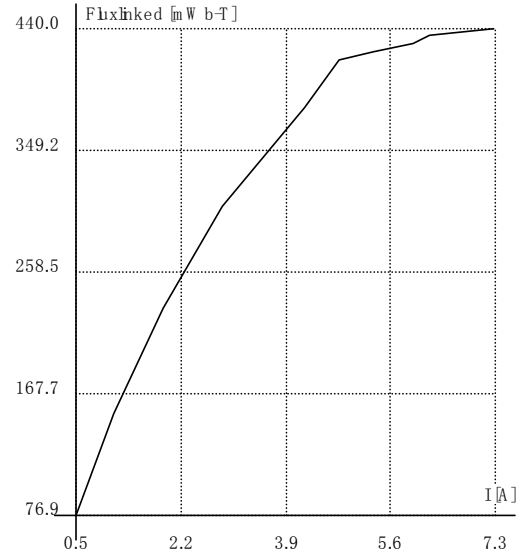


Fig. 8. The equivalent electrical circuit of a three-phase three-legged stacked-core transformer in the ATP.

A nonlinear inductance of type-98 in the ATP component library is used to simulate the saturation behavior of the core magnetic flux. The voltage-current characteristics of leg (L_1) and yoke (L_y) are firstly changed into flux-current characteristics using a subprogram called SATURATION. The flux-current characteristics of leg (L_1) and yoke (L_y) are shown in Fig. 9 and Fig. 10 respectively.

In order to demonstrate the effectiveness of the proposed switching strategy, we present three case studies for comparison considering residual flux and switching time.

1) *Case 1:* In this case, all three phases are energized simultaneously at $t = 0$ s with zero residual fluxes. The current waveforms of the three-phases are shown in Fig. 11. Since the


 Fig. 9. Flux-current characteristics ($\phi - I$ characteristics) of the leg, L_1 .

 Fig. 10. Flux-current characteristics ($\phi - I$ characteristics) of the yoke, L_y .

instant $t = 0$ s is the optimal time instant to energize phase A, the waveform of the inrush current in phase A has the smallest amplitude. Also, since the instant $t = 0$ s is neither an optimal time instant to switch on phase B nor phase C, the inrush currents in these two phases are much larger than the inrush current in phase A. However, the amplitudes of the inrush current waveforms decrease with time due to winding resistances.

2) *Case 2:* In this case, phases A, B, and C are energized at $t = 0$ s, 0.03065 s, and 0.05105 s time instants respectively for zero residual fluxes. These time instants are determined using the proposed approach. For example, the time instant 0.03065 s for energizing phase B can be viewed by comparing the waveforms of Fig 4 and Fig. 5. The inrush currents of the three phases are shown in Fig. 12.

3) *Case 3:* In this case study, the residual fluxes in phases A, B, and C are considered at 0%, 70% and -70% of their respective maximum prospective flux values. The delayed switching strategy proposed in section III is used since the

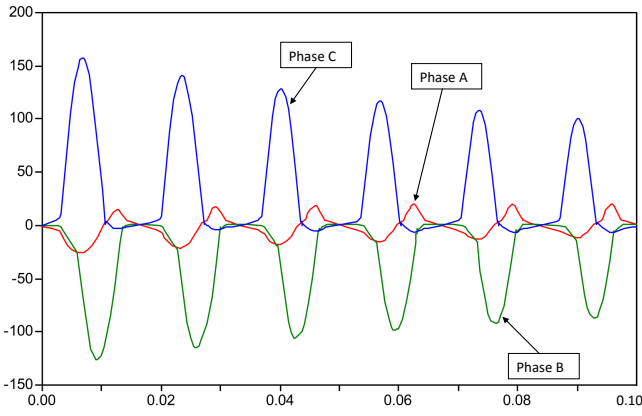


Fig. 11. Current waveforms for case 1.

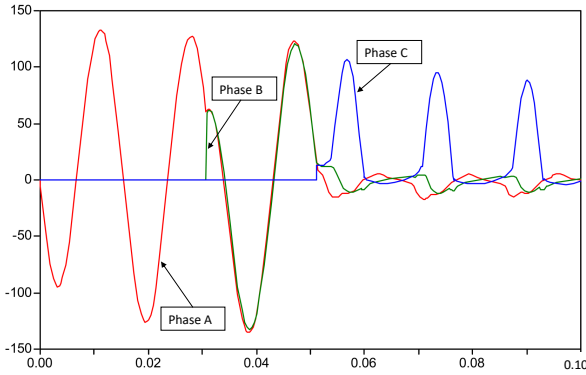


Fig. 12. Current waveforms for case 2.

fluxes are not zeros. Two sub-cases are considered as follows: (1) phases A, B, and C are energized at $t = 0$ s, 0.0967 s, and 0.11955 s time instants separately; (2) phases A, B, and C are energized at $t = 0$ s, 0.0967 s, and 0.0967 s time instants separately. Current waveforms for these two sub-case studies are shown in Fig. 13 and Fig. 14.

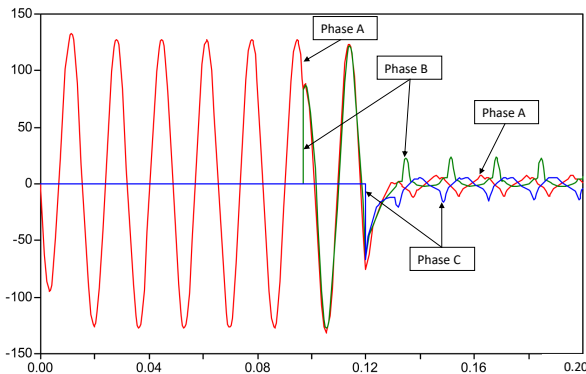


Fig. 13. Current waveforms for case 3, sub-case 1.

B. Experimental Validation

The approach was experimentally validated using the transformer shown in Fig. 7, as described here. The low voltage (120 V line to neutral) side of the transformer is supplied by a programmable power supply (Pacific Power Source UPC-3). The programmable power source enables precise control

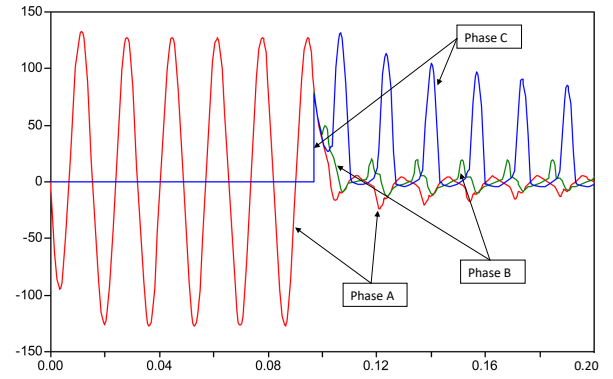


Fig. 14. Current waveforms for case 3, sub-case 2.

of voltage and frequency. It has several features for the efficient manipulation of power. Some of the features that were specifically used in the experiments include variable output voltage and variable phase angles. The power source also has meters on its front panel measuring the current, voltage, transients operation, power and power factor in each phase. It also has the capability to perform a waveform synthesis on any of the phase voltages or currents, returning the magnitudes of the harmonic components as well as their angles with respect to the fundamental frequency.

Figs. 15 and 16 show the simulated and actual current waveforms for an open-delta configuration with the low voltage (120 V) side energized at 40 V rms, line to neutral. The switching instants for the three phases were determined as before, by simulating prospective and dynamic flux waveforms and observing when they were equal. At this supply voltage, the instants were found to be $t = 0$ for phase A, $t = 30.65$ ms for phase B, and $t = 42.3$ ms for phase C. Residual fluxes were reduced to zero. In the experiment, this was achieved by first energizing all three phases with rated voltage, and gradually reducing the supply voltage to zero.

In the experimental current waveforms, it was noticed that the current in each phase started from the point where phase A was energized while they were programmed to start at different time instants. This happens because a three phase switch was used between voltage supply and transformer. When phase A was energized, there were induced voltages in phases B and C, because the current path was completed via the transformer to the supply through the switch. However after energization of phases B and C at their respective time instants, the actual phase currents appear in the measurements.

It was found that at rated supply voltage actual current waveforms deviated from simulated waveforms due to significant harmonic content which was not captured adequately by the simulated model. This was exacerbated with the delta closed. This is because the first closing phase has to magnetize the cores in all three phases, resulting in higher inrush current. However, the controlled switching is still effective in mitigating the inrush, even though they show larger harmonic distortion.

V. CONCLUSION

This paper has introduced a controlled switching scheme to reduce inrush currents in power transformers. Also, it has es-

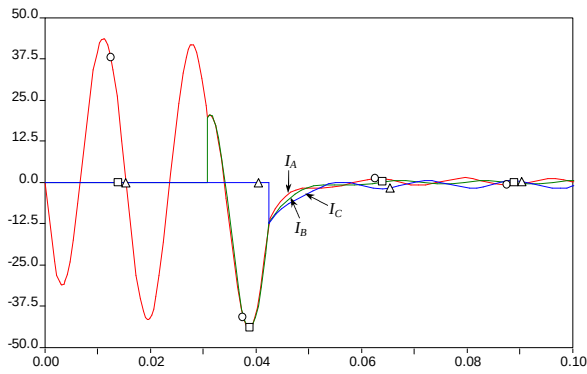


Fig. 15. Simulated waveform with 40 V supply, phases A, B, and C energized at 0, 30.65 ms and 42.3 ms.

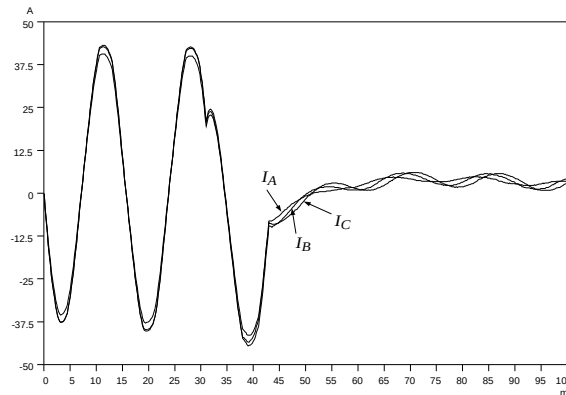


Fig. 16. Actual waveform with 40 V supply, phases A, B, and C energized at 0, 30.65 ms and 42.3 ms.

tablished a transient model for three-phase stacked core power transformers to simulate the change of flux. The transient model was developed based on the duality between electric and magnetic circuits where a non-linear inductance was used to simulate core saturation. The proposed scheme was tested on a real power transformer by means of simulations and the results were validated through laboratory experiments. The results show that the inrush currents are reduced significantly when the proposed scheme is used. Reducing inrush currents will reduce the complexity of transformer design and cost.

REFERENCES

- [1] J. H. Brunke and K. J. Frohlich, "Elimination of Transformer Inrush Currents by Controlled Switching—Part I: Theoretical Considerations," *IEEE Trans. Power Del.*, vol. 16, no. 2, p. 276280, Apr. 2001.
- [2] J. H. Brunke and K. J. Frohlich, "Elimination of Transformer Inrush Currents by Controlled Switching—Part II: Application and Performance Considerations," *IEEE Trans. Power Del.*, vol. 16, no. 2, pp. 281–285, Apr. 2001.
- [3] J. H. Brunke, "Elimination of transient inrush currents when switching power transformers," Ph.D. dissertation, Dept. Inf. Technol. Elect. Eng., Swiss Federal Inst. Technol., Zurich, 1998.
- [4] E. Cardelli, E. Della Torre, V. Esposito, and A. Faba, "Theoretical Considerations of Magnetic Hysteresis and Transformer Inrush Current," *IEEE Trans. on Magnetics*, vol. 45, no. 11, pp. 5247–5250, Nov. 2009.
- [5] P. C. Ling and A. Basak, "Investigation of Magnetizing Inrush Current in a Single-Phase Transformer," *IEEE Transactions on Magnetics*, vol. 24, no. 6, pp. 3217–3222, Nov. 1988.
- [6] K. S. Smith, L. Ran, and B. Leyman, "Analysis of Transformer Inrush Transients in Offshore Electrical Systems," *IEE Proceedings-Generation, Transmission and Distribution*, vol. 146, no. 1, pp. 89–95, Jan. 1999.

- [7] T. R. Specht, "Transformer Magnetizing Inrush Currents," *Electrical Engineering*, vol. 70, no. 4, pp. 324–324, Apr. 1951.
- [8] T. R. Specht, "Transformer Inrush and Rectifier Transient Currents," *IEEE Trans. on Power App. and Syst.*, vol. PAS-88, no. 4, pp. 269–276, Apr. 1969.
- [9] R. Yacimini and A. Abu-Nasser, "The Calculation of Inrush Current in Three-Phase Transformers," *IEE Proceedings B, Electric Power Applications*, vol. 133, no. 1, pp. 31–40, Jan. 1986.
- [10] S. Jazebi, F. De Leon, and N. Wu, "Enhanced Analytical Method for the Calculation of the Maximum Inrush Currents of Single-Phase Power Transformers," *IEEE Trans. Power Del.*, pp. 1–9, Earlu Access, 2015.
- [11] A. A. Adly, "Computation of Inrush Current Forces on Transformer Windings," *IEEE Trans. Magn.*, vol. 37, no. 4, pp. 2855–2857, Jul. 2001.
- [12] J. Ma, Z. Wang, Q. Yang, and Y. Liu, "Identifying Transformer Inrush Current Based on Normalized Grille Curve," *IEEE Trans. Power Del.*, vol. 26, no. 2, pp. 588–595, Apr. 2011.
- [13] A. M. Gaouda and M. M. A. Salama, "DSP Wavelet-Based Tool for Monitoring Transformer Inrush Currents and Internal Faults," *IEEE Trans. Power Del.*, vol. 25, no. 3, pp. 1258–1267, Jul. 2010.
- [14] L. F. Blume, G. Camilli, S. B. Farnham, and H. A. Peterson, "Transformer Magnetizing Inrush Currents and Influence on System Operation," *Transactions of the American Institute of Electrical Engineers*, vol. 63, no. 6, pp. 366–375, Jun. 1944.
- [15] M. Steurer and K. Frohlich, "The Impact of Inrush Currents on the Mechanical Stress of High Voltage Power Transformer Coils," *IEEE Trans. Power Del.*, vol. 17, no. 1, pp. 155–160, Jan. 2002.
- [16] M. A. Abdul Rahman, T. T. Lie, and K. Prasad, "The Effects of Short-Circuit and Inrush Currents on HTS Transformer Windings," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 2, pp. 5 500 108–5 500 108, Apr. 2012.
- [17] C. D. Hayward, "Prolonged Inrush Currents with Parallel Transformers Affect Differential Relaying," *Transactions of the American Institute of Electrical Engineers*, vol. 60, no. 12, pp. 1096–1101, Dec. 1941.
- [18] J. P. Bowles, "Overvoltages in HV DC Transmission Systems Caused by Transformer Magnetizing Inrush Currents," *IEEE Trans. on Power App. and Syst.*, vol. PAS-97, no. 4, pp. 487–495, Mar. 1974.
- [19] R. Dogan, S. Jazebi, and F. de Leon, "Investigation of Transformer-Based Solutions for the Reduction of Inrush and Phase-Hop Currents," *IEEE Trans. Power Electron.*, pp. 1–10, Earlu Access, 2015.
- [20] M. Nagpal, T. G. Martinich, A. Moshref, K. Morison, and P. Kundur, "Assessing and Limiting Impact of Transformer Inrush Current on Power Quality," *IEEE Trans. Power Del.*, vol. 21, no. 2, pp. 890–896, Apr. 2006.
- [21] N. Chiesa and H. K. Hidalen, "Novel Approach for Reducing Transformer Inrush Currents: Laboratory Measurements, Analytical Interpretation and Simulation Studies," *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 2609–2616, Oct. 2010.
- [22] J. V. Leite, A. Benabou, and N. Sadowski, "Transformer Inrush Currents Taking Into Account Vector Hysteresis," *IEEE Trans. Magn.*, vol. 46, no. 8, pp. 3237–3240, Aug. 2010.
- [23] M. G. Vanti, S. L. Bertoli, S. H. L. Cabral, A. G. Gerent, and P. P. Kuo, "Semiaanalytic Solution for a Simple Model of Inrush Currents in Transformers," *IEEE Trans. Magn.*, vol. 44, no. 6, pp. 1270–1273, Jun. 2008.
- [24] E. Cardelli, A. Faba, and F. Tissi, "Prediction and Control of Transformer Inrush Currents," *IEEE Trans. Magn.*, vol. 51, no. 3, pp. 8 400 304–8 400 304, Mar. 2015.
- [25] E. Cardelli and A. Faba, "Numerical Modeling of Transformer Inrush Currents," *Physica B: Physics of Condensed Matter*, vol. 435, pp. 116–119, Feb. 2014.
- [26] R. A. Naghizadeh, B. Vahidi, and S. H. Hosseini, "Modelling of Inrush Current in Transformers Using Inverse Jiles-Atherton Hysteresis Model with a Neuro-Shuffled Frog-Leaping Algorithm Approach," *IEE Electric Power Applications*, vol. 6, no. 9, pp. 727–734, Nov. 2012.
- [27] X. Wang, D. W. P. Thomas, M. Sumner, J. Paul, and S. H. L. Cabral, "Characteristics of Jiles—Atherton Model Parameters and Their Application to Transformer Inrush Current Simulation," *IEEE Trans. Magn.*, vol. 44, no. 3, pp. 340–345, Mar. 2008.
- [28] L. Cipicigan, W. Xu, and V. Dinavahi, "A New Technique to Mitigate Inrush Current Caused by Transformer Energization," in *IEEE Power Engineering Society Summer Meeting*, vol. 1, Chicago, IL, USA, July 2002, pp. 570–574.
- [29] C.-K. Cheng, T.-J. Liang, J.-F. Chen, S.-D. Chen, and W.-H. Yang, "Novel Approach to Reducing the Inrush Current of a power Transformer," *IEE Proceedings - Electric Power Applications*, vol. 151, no. 3, pp. 289–295, May 2004.

- [30] N. Aeron, "Reduction of Inrush Currents in three Phase Transformer Units using a Controlled Switching Scheme," Master's thesis, Dept. Elect. Comput. Eng., North Dakota State University, Fargo, North Dakota, 2004.
- [31] H.-T. Tseng and J.-F. Chen, "Voltage Compensation-Type Inrush Current Limiter for Reducing Power Transformer Inrush Current," *IET Electric Power Applications*, vol. 6, no. 2, pp. 101–110, Feb. 2012.
- [32] H.-C. Seo, C.-H. Kim, S.-B. Rhee, J.-C. Kim, and O.-B. Hyun, "Superconducting Fault Current Limiter Application for Reduction of the Transformer Inrush Current: A Decision Scheme of the Optimal Insertion Resistance," *IEEE Trans. Appl. Supercond.*, vol. 20, no. 4, pp. 2255–2264, Aug. 2010.
- [33] D. I. Taylor, J. D. Law, B. K. Johnson, and N. Fischer, "Single-Phase Transformer Inrush Current Reduction Using Prefluxing," *IEEE Trans. Power Del.*, vol. 27, no. 1, pp. 245–252, Jan. 2012.
- [34] V. Molcette, J.-L. Kotny, J.-P. Swan, and J.-F. Brudny, "Reduction of Inrush Current in Single-Phase Transformer Using Virtual Air Gap Technique," *IEEE Trans. Magn.*, vol. 34, no. 4, pp. 1192–1194, Jul. 1998.
- [35] K. Yabe, "Power Differential Method for Discrimination Between Fault and Magnetizing Inrush Current in Transformers," *IEEE Trans. Power Del.*, vol. 12, no. 3, pp. 1109–1118, Jul. 1997.
- [36] B. Kovan, F. de Leon, D. Czarkowski, Z. Zabar, and L. Birenbaum, "Mitigation of Inrush Currents in Network Transformers by Reducing the Residual Flux With an Ultra-Low-Frequency Power Source," *IEEE Trans. Power Del.*, vol. 26, no. 3, pp. 1563–1570, Jul. 2011.
- [37] H. Shimizu, K. Mutsuura, Y. Yokomizu, and T. Matsumura, "Inrush-Current-Limiting With High T_C Superconductor," *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, pp. 2071–2073, Jun. 2005.
- [38] S. M. Madani, M. Rostami, G. B. Gharehpetian, and R. Haghmaram, "Inrush Current Limiter based on Three-Phase Diode Bridge for Y-yg Transformers," *IET Electric Power Applications*, vol. 6, no. 6, pp. 345–352, Jul. 2012.
- [39] T. Ghanbari and E. Farjah, "Efficient Resonant-Type Transformer Inrush Current Limiter," *IEE Proceedings - Electric Power Applications*, vol. 6, no. 7, pp. 429–436, Aug. 2012.
- [40] M. Tarafdar Hagh and M. Abapour, "DC Reactor Type Transformer Inrush Current Limiter," *IEE Proceedings - Electric Power Applications*, vol. 1, no. 5, pp. 808–814, Sept. 2007.
- [41] J.-F. Chen, T.-J. Liang, C.-K. Cheng, S.-D. Chen, R.-L. Lin, and W.-H. Yang, "Asymmetrical Winding Configuration to Reduce Inrush Current with Appropriate Short-Circuit Current in Transformer," *IEE Proceedings - Electric Power Applications*, vol. 152, no. 3, pp. 605–611, Jun. 2005.
- [42] Y. Cui, S. G. Abdulsalam, S. Chen, and W. Xu, "A Sequential Phase Energization Technique for Transformer Inrush Current Reduction—Part I: Simulation and Experimental Results," *IEEE Trans. Power Del.*, vol. 20, no. 2, pp. 943–949, Apr. 2005.
- [43] W. Xu, S. G. Abdulsalam, Y. Cui, and X. Liu, "A Sequential Phase Energization Technique for Transformer Inrush Current Reduction—Part II: Theoretical Analysis and Design Guide," *IEEE Trans. Power Del.*, vol. 20, no. 2, pp. 950–957, Apr. 2005.
- [44] S. G. Abdulsalam and W. Xu, "A Sequential Phase Energization Method for Transformer Inrush Current Reduction—Transient Performance and Practical Considerations," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 208–216, Jan. 2007.
- [45] Yu-Hsing Chen, Ming-Yang Yeh, Po-Tai Cheng, Jen-Chuan Liao, and Wen-Yin Tsai, "An Inrush Current Reduction Technique for Multiple Inverter-Fed Transformers," *IEEE Trans. Ind. Appl.*, vol. 50, no. 1, pp. 474–483, Jan. 2014.
- [46] X. Chen, "A Three-Phase Multi-Legged Transformer Model in ATP Using the Directly-Formed Inverse Inductance Matrix," *IEEE Trans. Power Del.*, vol. 11, no. 3, pp. 1554–1562, Jul. 1996.
- [47] B. A. Mork, "Five-Legged Wound-Core Transformer Model: Derivation, Parameters, Implementation and Evaluation," *IEEE Trans. Power Del.*, vol. 14, no. 4, pp. 1519–1526, Oct. 1999.
- [48] X. Chen and S. S. Venkata, "A Three-Phase Three-Winding Core-Type Transformer Model for Low-Frequency Transient Studies," *IEEE Trans. Power Del.*, vol. 12, no. 2, pp. 775–782, Apr. 1997.
- [49] B. A. Mork, F. Gonzalez, D. Ishchenko, D. L. Stuehm, and J. Mitra, "Hybrid Transformer Model for Transient Simulation—Part I: Development and Parameters," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 248–255, Jan. 2007.
- [50] B. A. Mork, F. Gonzalez, D. Ishchenko, D. L. Stuehm, and J. Mitra, "Hybrid Transformer Model for Transient Simulation—Part II: Laboratory Measurements and Benchmarking," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 256–262, Jan. 2007.
- [51] A. Pors and N. Browne, "Modelling the Energisation of a Generator Step-up Transformer from the High Voltage Network," in *Australasian Universities Power Engineering Conference*, Sydney, NSW, Australia, Dec. 2008, pp. 1–5.
- [52] D. P. Balachandran, R. S. Kumar, and V. P. Shimnamol, "Transformer Inrush Current Reduction by Power Frequency Low Voltage Signal Injection to the Tertiary Winding," in *IEEE Lausanne Power Tech*, Lausanne, Switzerland, July 2007, pp. 1953–1958.
- [53] C. Zhe, Y. W., and L. Guojun, "Improved Modelling and Calculation on Electromagnetic Transient of Power Transformer," in *CES/IEEE 5th International Power Electronics and Motion Control Conference, IPEMC*, vol. 2, Shanghai, China, Aug. 2006, pp. 1–6.
- [54] S. Sendilkumar, B. L. Mathur, and J. Henry, "A New Technique to Classify Transient Events in Power Transformer Differential Protection Using S-Transform," in *International Conference on Power Systems*, Kharagpur, India, Dec. 2009, pp. 1–6.
- [55] J. Mitra, X. Xu, and M. Benidris, "A controlled switching approach to reduction of three-phase transformer inrush currents," in *IEEE Industry Applications Society Annual Meeting (IAS)*, Portland, OR, USA, Sept. 2018, pp. 1–7.
- [56] "Alternative Transients Program (ATP)." [Online]. Available: <https://www.atpdraw.net/>
- [57] E. C. Cherry, "The Duality between Interlinked Electric and Magnetic Circuits and the Formation of Transformer Equivalent Circuits," in *Physical Society*, vol. 62, 1949, pp. 101–111.



Joydeep Mitra (S'94–M'97–SM'02–F'19) received the B.Tech. (Hons.) degree in electrical engineering from the Indian Institute of Technology Kharagpur, Kharagpur, India, in 1989, and the Ph.D. degree in electrical engineering from Texas A&M University, College Station, TX, USA, in 1997.

He is currently an Associate Professor of electrical engineering with Michigan State University, East Lansing, MI, USA, the Director of the Energy Reliability and Security Laboratory, and a Senior Faculty Associate with the Institute of Public Utilities. He is a Fellow of the IEEE and recipient of the 2019 IEEE-PES Roy Billinton Power System Reliability Award. He is co-author of the book, "Electric Power Grid Reliability Evaluation: Models and Methods," and of IEEE Standard 762. His research interests include reliability, planning, stability, and control of power systems.



Xufeng Xu received the B.E. and Ph.D. degrees in electrical engineering from Zhejiang University, Hangzhou, China, in 2004 and 2009 respectively.

He is currently working at American Electric Power, New Albany, OH, USA. His research interests include microgrid reliability, power system planning, optimization algorithms, renewable energy integration and EMS.



Mohammed Benidris (S'10–M'14) received a Ph.D. degree in Electrical Engineering from Michigan State University in 2014, and MSc. and BSc. degrees in Electrical Engineering from University of Benghazi, Libya in 2005 and 1998 respectively.

He is an Assistant Professor of Electrical Engineering with the University of Nevada, Reno (UNR), Reno, NV, USA. Prior to joining the UNR, he was Research Associate and Visiting Lecturer at Michigan State University. Prior to this, he was an Assistant Lecturer at the department of Electrical and Electronics Engineering, University of Benghazi, Benghazi, Libya. His main research interests include power system reliability and stability and resilience of cyber-physical energy systems.