Varying the energisation condition to mitigate sympathetic inrush current

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Article Info

Article history:

Received Oct 11, 2022
Revised Apr 5, 2023
Accepted Apr 7, 2023

Keywords:

Energisation
Magnetising inrush current
Power system computer aided design
Sympathetic inrush current
Three transformers

ABSTRACT

Transformers are generally easy to access and can contribute significantly to entire power system. When a transformer is turned on for the first time, it produces a magnetising inrush current which acts as a starting current. Energisation of transformer has a substantial impact on inrush current and transformer that are connected in parallel. Sympathetic inrush current is a phenomenon that appears when a transformer is switched-on in network whereas the other transformers that was earlier energised. Besides, when sympathetic inrush phenomena occur, the peak and period fluctuate significantly. In this paper, the transformers will be energised in three different ways and each condition will be explored in depth. The operation time of the transformer's energisation whether it is energised simultaneously or at different times are tested and analysed in terms of their characteristics. It is performed using power system computer aided design (PSCAD) software, starting with a develop model of the energisation and then generate the outcomes. The results of the simulation demonstrate that energising the transformer in different ways can give different effect on the sympathetic inrush current, as well as the variables that affect it and methods for reducing it.

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1. INTRODUCTION

In the modern world, human growth is depending on the consistent and reliable electrical supply. The world has begun to change dramatically in sources, applications and its power [1]. The industry is concentrated on advancing the integration of renewable energy into existing system which can help to lower the cost of power production and improve the power quality. Other than that, the transformer is an expensive piece of equipment based on their stability, reliability and availability, transformers play a crucial role in the entire overall power system and energy utilities that are generally controlled by difference relays [2]–[6]. There are negative impacts when the population of the network participants expands and the regularity of the network modifications which is the sympathetic inrush current is more noticeable and becomes more severe. Since the sympathetic inrush current occurs when the transformers are attached in parallel with the affected transformers [7], the sympathetic inrush current has not given top priority to investigate in the last few years. In a wind farm, wind turbine transformer (WTT) is vital machinery which operate as step-up transformers to connect grid system with the with the wind turbines. As previously described in [8], [9] a three-phase dry-type transformer known as WTT is located at the base of wind turbine towers, either are outside or inside.

According to [9], one of the challenges faced by wind turbine transformer is the shifting nature of wind that served as its primary source. The unpredictable behaviour of wind might result in the wind turbine transformer being disconnected and connected repeatedly. It might result a regular overvoltage and overcurrent on the wind turbine transformer that majority supplied from the collection grid. Overcurrent is the biggest risk of the inrush current since it has a potential that can cause a major damage in a variety of electrical equipment. Due to the transformer's core saturation, the inrush current is produced and can be divided into two types which is magnetising and sympathetic inrush current [4]. An early effort [10], [11], observed that any electrical equipment close to energised transformer will be interrupted by the inrush current and the inrush current from a transformer might cause the transformer relay protection to mal-operation [4], [5], [12]–[15]. Unfortunately, the existence of many transformers in a wind farm aggravates these problems since it not only activates two transformers at once, but it energised multiple transformers. As outcome, the sympathetic inrush current is becoming more frequent, requiring the researchers to investigate and determine the best method to reduce them.

Figure 1 shows the block diagram which starting with the objectives of the project to mitigate the sympathetic inrush current. To model the transformers, it is necessary to determine the parameters. Other than that, the energisation of transformers come in three different ways such as by energising one transformer while switched-on two transformers, by energising two transformers and switched-on one transformer and last but not least is energising three transformers simultaneously. Furthermore, the operation time of a transformer's energisation is evaluated and analysed whether it is energised simultaneously or at various times. Power system computer-aided design (PSCAD) software is chosen for modelling simulation tool since it is regularly used and used to develop modelling of the energising study and obtain the simulation results between three transformers. Following with the analysis and conclusion, the simulation findings will be discussed.

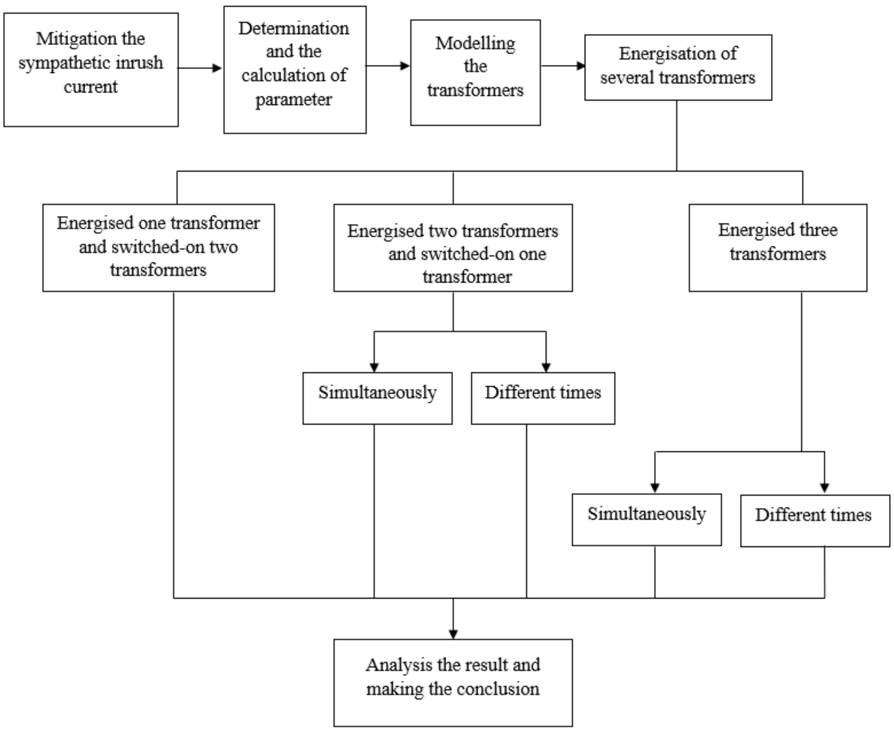

Figure 1. The block diagram of modelling and simulation project

One of the most challenging issues in the power systems is power system transients that produced by the energisation of large transformers. The transformer energisation can be caused numerous difficulties and a variety of issues, including inrush current, voltage dips and others [5], [8], [16]. Over the past decade, the major difficulty of detecting the transformer transients particularly is inrush current. When a transformer is turned on for the first time, a magnetising inrush current is developed in a transformer by generating a highest current and surpassing the rated current [2].

When a single transformer is switched-on without any additional transformers that are connected to the power supply, the inrush current is [17]–[19]. The magnetising inrush current also can develop once energising a no-load transformer during the energisation [20], [21]. An earlier researchers discussed that the major characteristic of the magnetising inrush current is it spikes extremely high but progressively decays after a few cycles [17], [22] before the current drops to zero [7] as shown in Figure 2. Other than that, the value of magnetising inrush current can be several times greater than the rated current [6], [19], [23]–[25]. An early effort [6], presented that under typical condition, the inrush current only in a short duration means that it do not allow to serious damage for the transformer. However, continuous and repeated magnetising inrush current can cause transformer winding to become brittle, which will shorten the equipment's lifespan and diminishes the power quality [6], [19]. Due to the growing use of power loads, power quality issues are serious concern [26], [27]. In addition, inrush current is divided into three categories and the differences between three types of inrush current are shown in Table 1.

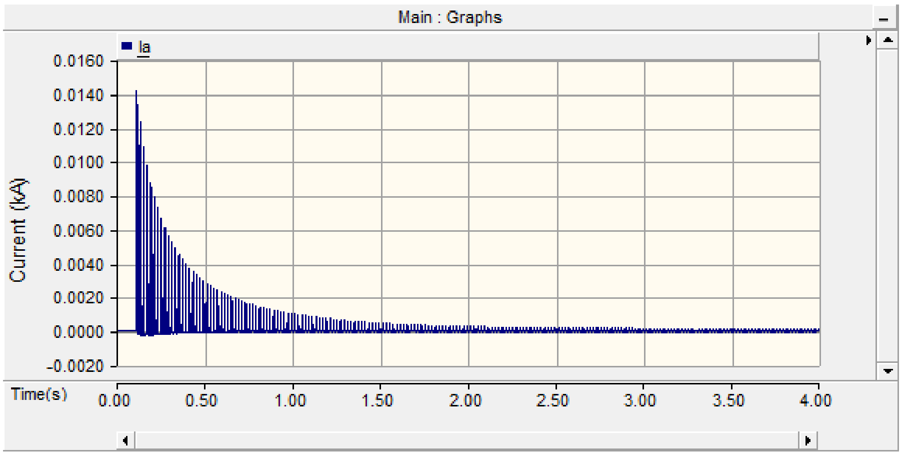

Figure 2. The magnetising inrush current waveform in a single transformer

Table 1. Three types of inrush current [23], [24], [28], [29]

Inrush Current	Definition
Energisation inrush current	Generated by reapplying a voltage to a transformer that had previously been de-energised
Recovery inrush current	Produced by the restoration of voltage after a fault has been cleared
Sympathetic inrush current	Once the transformers are turned on and having the other transformer that was previously energised

Next, the sympathetic inrush current is develop when the transformers are operating in parallel, [5], [11], [30] and involves two or more transformers whereas the voltage supply are applied to each of the transformers [28], [31]. In the same way, when energising a transformer in a circuit and having other transformers that previously been energised, the sympathetic inrush current are developed [5], [13], [31]. Due to the highest emergence of the transformer in a power system, the issues getting worse by the sympathetic inrush current because it is energising more than two transformers at the same times. Switching and energising all the transformers also could be simultaneously. As a result, the sympathetic inrush current is becoming more frequent, causing researchers to look for strategies to lessen and eliminate it.

There are two transformers that are connected in parallel as shown in Figure 3. When the T1 is already in operation and T2 is connected to the network, the transient inrush current flows both through T2 and T1 at the same time. T2 are typically not loaded during these energisation periods, and once the inrush current is shared, the sympathetic inrush current phenomenon is defined [17], [22].

One of the characteristics of the sympathetic inrush current is when the current is increase, it does not hit to the maximum level and are increases slowly but once the current is dissipating, it decrease slowly persists for a long times [17], [22], [30]. Figure 4 represent a green colour for magnetising inrush current and the blue colour is for sympathetic inrush current waveform. The characteristics between two waveform is having an opposite direction which means not overlapping with each other as shown below.

The magnitude of the sympathetic inrush current can be affected by adjusting the factors either increasing or reducing the value. The sympathetic inrush current is divided into a few sections which influenced by a number of factors. There are consists of three factors which is system resistance, load and power factor and switching-on angle and a short explanation will be presented [7], [17], [22].

a) System resistance: Based on the observation, the rises and the decrease of sympathetic inrush current are influenced by system resistance [32]. It is necessary to adjust the sympathetic inrush current growth by changing the value of the system resistance that might affect the sympathetic inrush current waveform. Other than that, the system resistance will reduce the magnitude of peak inrush current and quicken the inrush current decay [7]. As a result, it has been discovered that the higher system resistance, the sympathetic inrush will persist and develop more quickly.
b) Load and power factor: A thorough understanding of inrush current is required to assess and study the effects of the transformer because it is regularly connected to the load [33]. This is because the transformer usually connects to the load. When the transformer is running with a full load that has a power factor near to unity, the maximum values for sympathetic and magnetising inrush currents are significantly decreased compared to no-load conditions [17], [22]. Furthermore, even when the transformers are not loaded, both inrush currents are constantly expanding. As a result, the load current of the switching transformer has little impact on the magnitude and duration of inrush current because the inrush current may decrease when the load is very high [17].
c) Switching-on angle: The switching-on angle also has an impact on the sympathetic inrush current's magnitude [17], [22], [33], [34]. The magnitude of the sympathetic inrush current is decrease when the switching-on angle is raised 90 degrees. On the other hand, once the switching-on angle is set to 0 degrees, the sympathetic inrush current begins to appear and persists. The sympathetic inrush current is grown on the other sides once is set to 180 degrees. According to the concept, the sympathetic inrush current decreases as the switching-on angle increases until it reaches the opposite direction.

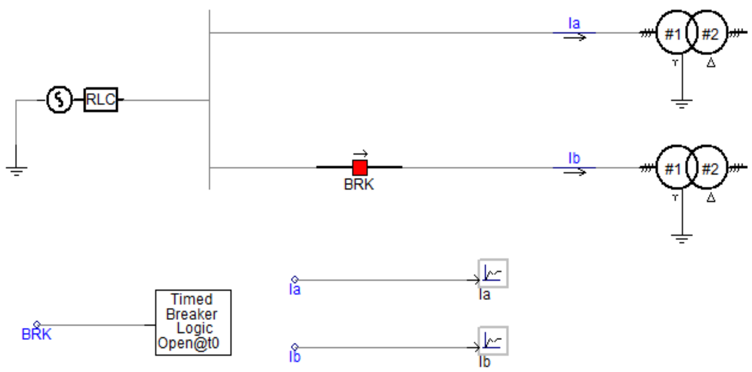

Figure 3. The schematic circuit for sympathetic inrush current by using two transformers

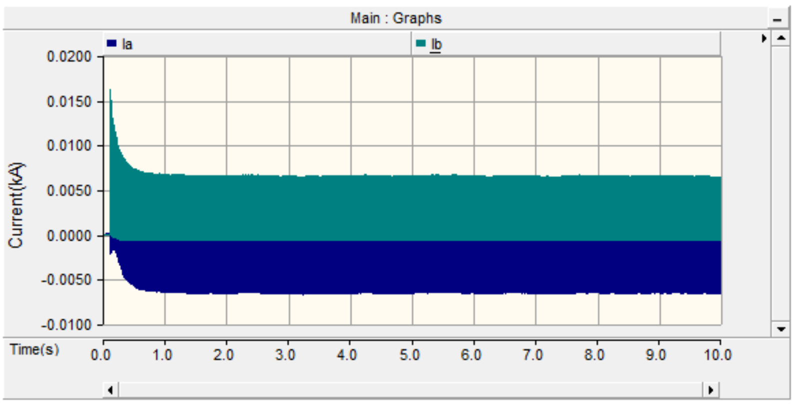

Figure 4. Sympathetic inrush current waveform

2. THE PROPOSED METHOD

The wye-delta of single-line (circles) transformer is the types of the transformers that are utilised in this modelling and all of the parameters for the transformers are listed in Table 2. The three transformers that having a same rating is used which is 100 kVA, 11/0.415 kV. This section is explained a further detailed what happens to the waveforms and measurement of the sympathetic inrush current when the transformers are energised at different times or energised simultaneously. Other than that, there are three different conditions which is by having only one circuit breaker in modelling design, two circuit breakers and three circuit breakers. The sympathetic inrush current is influenced differently by each condition.

Table 2. The parameters of the transformers modelling

Parameters	Value
Transformers	100 kVA, 11/0.415 kV
Resistance	20 Ω
Inductance	0.5 H
Capacitance	100 F
Frequency	50 Hz

3. METHOD

All the circuit breakers are connected in parallel with the three transformers. The circuit breaker is represented by (BRK) in the simulation design below and the circuit breaker's operation time is determined by timed breaker logic. Other than that, the transformers can be energised in three distinct methods which is energised one transformer and switched-on two transformers, energised two transformers and switched-on one transformer and energised three transformers. In addition, there also divided into two conditions which is energised simultaneously or different times. All the conditions will be discussed in great details. In this section also provided how the peak value of sympathetic inrush current might be affected by the energisation of transformers.

3.1. Energised one transformer and switched-on two transformers

As illustrated in Figure 5, it shows that the T1 and T2 are already in operation which is there is no circuit breaker is connected to the T1 and T2. The energisation of the transformer is only happened in T3 since the circuit breaker 1 (BRK1) is only attached to the T3. The operation time for BRK1 is set to 0.01 s.

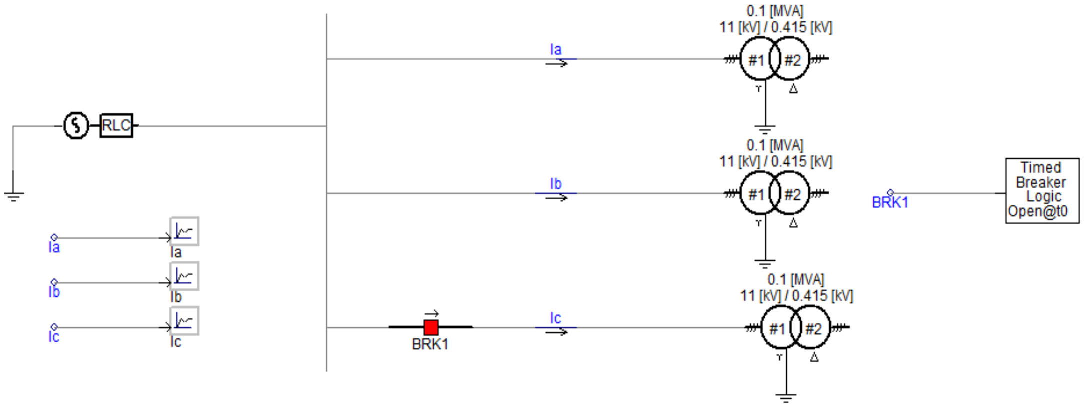

Figure 5. The simulation circuit of one circuit breaker and three transformers

3.2. Energised two transformers and switched-on one transformer

Figure 6 demonstrates that circuit breakers are applied to T2 and T3, but not to T1 which is not applied to any circuit breakers. For this connection, the operation time is separated into two cases. The first case is the operation time are set into 0.01 s for both circuit breakers. The second case occurs when the operation time are set into two different times whereas 0.01 and 0.05 s.

3.3. Energised three transformers

Additionally, by using three transformers with a circuit breaker are connected to each transformer as shown in Figure 7. For this design, the operation time are divided into three parts which is BRK1, BRK2 and BRK3. Then, for the simulation result are classified into two categories which is by energised simultaneously and energised in various times.

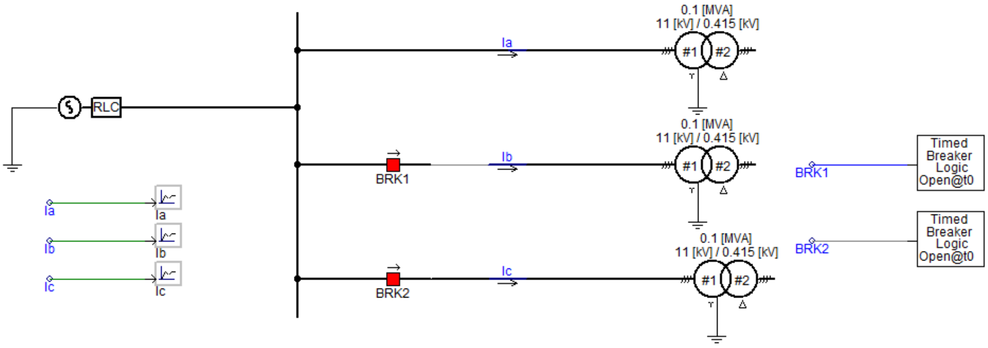

Figure 6. The simulation circuit of two circuit breakers and three transformers

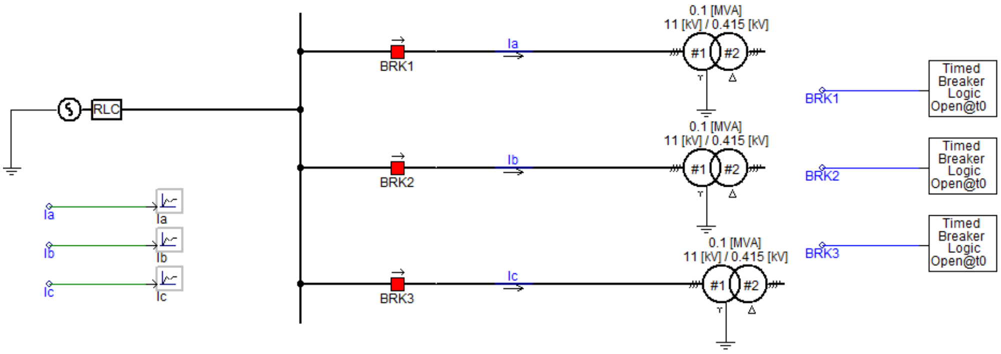

Figure 7. The schematic circuit of three circuit breakers and three transformers

4. RESULTS AND DISCUSSION

4.1. T3 is energised, T1 and T2 are switched-on

There are two transformers which is T1 and T2 that are currently in operation. Once the T3 is energised in 0.01 s while the other transformer in operation, the sympathetic inrush current will be develop as shown in Figure 8. As can be seen, the sympathetic inrush current achieves a minimum value of -0.6100 A. Besides, the sympathetic inrush current remains constant and decays slowly, which taking 8 s to meet -0.1350 A before reaching steady-state.

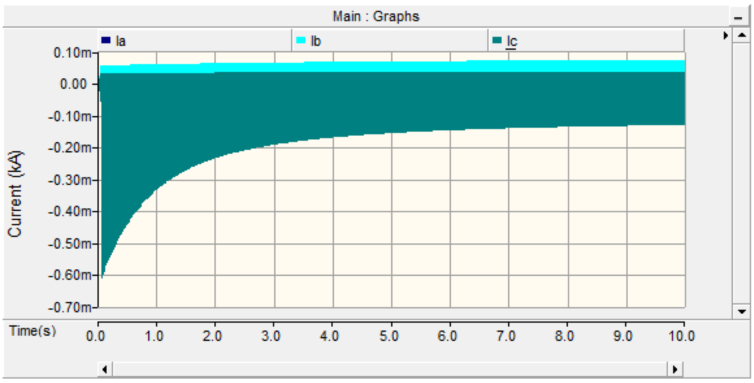

Figure 8. The simulation result by energising only one transformer

4.2. T2 and T3 energised simultaneously, T1 is switched-on

The operation time for both circuit breakers is set to 0.01 s and both currents are started to energise at the same moment. Focus on the simulation results, the sympathetic inrush current hits a high of -0.4600 A which in small value. As it can see in Figure 9, the current started to drop because in 8 s the sympathetic inrush current reached -0.0850 A before becoming continuous. The characteristic of the waveform is having a larger magnitude and is decreasing slowly.

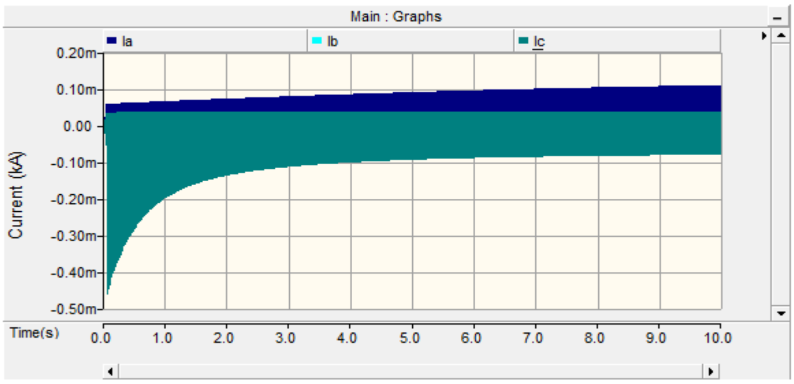

Figure 9. The simulation result by energising two transformers simultaneously

4.3. T2 and T3 energised in different times, T1 is switched-on

Figure 10 depicts the simulation results obtained by setting the operation time of the circuit breaker in different times. For this BRK1 takes 0.01 s to operate, while BRK2 takes 0.05 s. Since the T2 and T3 is energised by having the other transformer that already in operation, the sympathetic inrush current is growing. The waveform has a characteristic that resemble a magnetising inrush current but in the opposite directions. Even though it is appearing to be a magnetising inrush current, it never approaches 0 A and persist for a long duration. From the results, the sympathetic inrush current began to grow in 0.01 s and directly reached -16.6 A at its peak. Other than that, the current start to decay rapidly but after 1.0 s, it begins to stabilise.

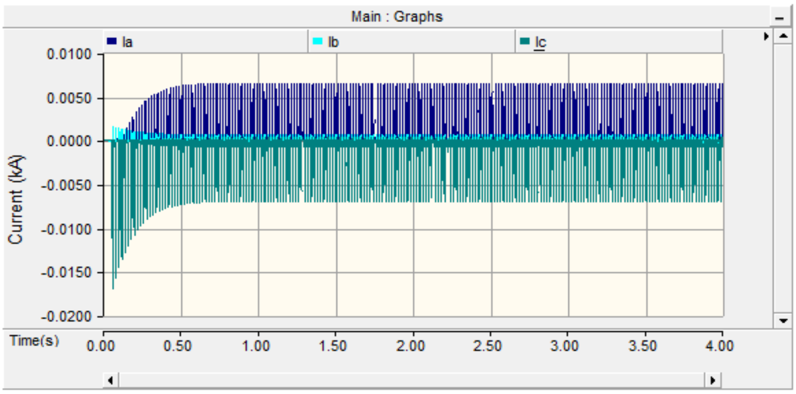

Figure 10. The simulation result by energising two transformers at different times

4.4. T1, T2 and T3 turned on simultaneously

Figure 11 shows the simulation by energising all the three transformers simultaneously at 0.01 s. As it can be observed that the peak of the current is -0.3618 A at 0.01 s. The magnitude of the waveform is likewise smaller and it is decaying faster in 9 s, indicating that the sympathetic inrush current has already reached -0.0580 A and the current is approaching steady-state. The waveform is identical to that magnetising inrush current but in the opposite direction.

4.5. T1, T2 and T3 turned on in different times

Additionally, there are three transformers are used with circuit breakers that are operated at various times and are each connected to a different transformer. BRK1 has an operation time of 0.1 s, BRK2 of 0.5 s, and BRK3 of 1.0 s. Figure 12 shows that when the T1 is turned on for the first time without any other transformers operating, a magnetising inrush current occurs. When the BRK2 is closed, which occurs after

0.5 s, the magnetising inrush current starts at 0.1 s and lasts until it reaches 15 A before starting to decline. The sympathetic inrush current then occurs for this system at 0.5 s after the T2 is energised, whereas the T1 was already in operation. The sympathetic inrush current only develops in low value, which is roughly around -2 A, while the magnetising inrush current starts at 0.5 s and peaks at 17 A. The T3 begins to energise after 1.0 s, and the highest peak current is 17.7 A. Since the magnetising inrush current is declining but not reaching 0 A, the sympathetic inrush current exists for the entire system and persist for a long duration.

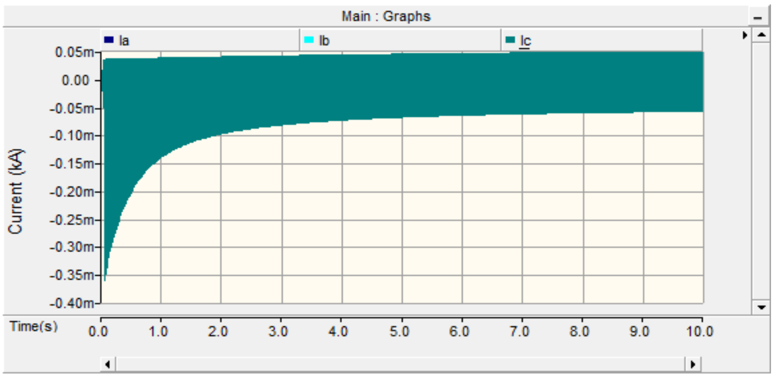

Figure 11. The simulation result by energising three transformers simultaneously

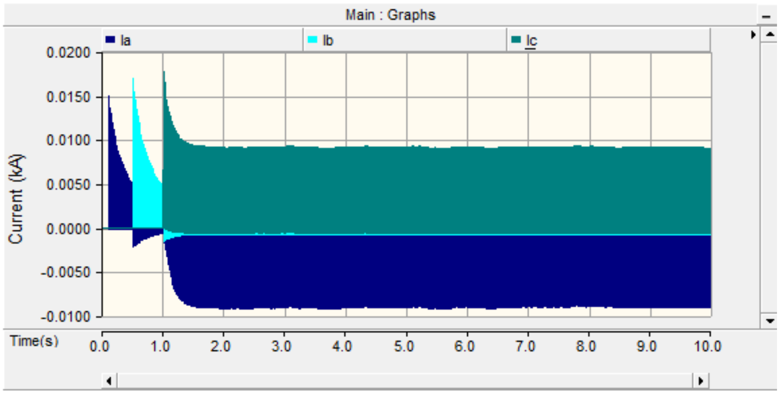

Figure 12. The simulation results by energising three transformers at different times

4.6. Discussion

Transformers are the essential equipment in a wind farm. The sympathetic inrush current is becoming more severe since the wind farm use many wind turbine transformers and the parallel connection between the wind turbine transformers making this situation much worse which is it energising more than two transformers at once. These sections are explaining an effective method of energising the transformers with the least amount of the sympathetic inrush current. Table 3 shows the condition of the transformers and the maximum value of the sympathetic inrush current that developed. According to the table, the higher value of sympathetic inrush current is occurred in 4.5 when all the three transformers are energised but in various operation times which is energised at 0.1, 0.5 and 1.0 s. However, the current began to decay and reached 9.2 A in 2 s whereas the current are decays faster, as seen in Table 4. It is advisable to avoid energising the three transformers at different times because the maximum peak is 17.7 A which is too high and even in steady-state, it still in a higher value. The minimum value of sympathetic inrush current is 4.4 which is -0.3618 A where all the three transformers are energised simultaneously at 0.01 s. Unfortunately, by comparing to the other four situations, the inrush current decreases quite slowly, needing 9 s to meet -0.0585 A before achieving steady-state.

As indicated in Table 3, it can see how the quantity of already in operation transformers that having the same operating time can affected the peak of sympathetic inrush current. From this simulation results, the peak of sympathetic inrush current for one transformer that already in operation is -0.4600 A. The peak value is bigger at two transformers that previously in operation which is -0.6100 A. On the other hand, the maximum value of sympathetic inrush current for 4.4 is -0.3618 A whereas it does not have any transformer that already switched-on. It is observed that when the number of transformers that already in operation is increase, the peak of sympathetic inrush current that appears also increase.

In summary, energising two transformers and one transformer that is already switched-on is an effective method of energising the transformers that produces the least amount of sympathetic inrush current. This condition is recommended since it has the fewest amount of transformers in use while maintaining the same operating times. Furthermore, when the operation time is varied to different times, the highest peak is not too high. The time taken to decay and achieves steady-state is similarly shorter which only taking only 1 s as can be seen in Table 4.

Table 3. The condition of the transformers and the peak values of the sympathetic inrush currents

Conditions	T1	T2	T3	Value at peak (A)
4.1	Already in operation	Already in operation	Energised at 0.01 s	-0.6100 A
4.2	Already in operation	Energised at 0.01 s	Energised at 0.01 s	-0.4600 A
4.3	Already in operation	Energised at 0.01 s	Energised at 0.05 s	-16.6 A
4.4	Energised at 0.01 s	Energised at 0.01 s	Energised at 0.01 s	-0.3618 A
4.5	Energised at 0.1 s	Energised at 0.05 s	Energised at 1.0 s	17.7 A

Table 4. The time and value of the sympathetic inrush currents once reach steady-state

Conditions	Current at steady-state (A)	Time to reach steady-state (s)
4.1	-0.1350 A	8 s
4.2	-0.0850 A	8 s
4.3	-7.0 A	1 s
4.4	-0.0585 A	9 s
4.5	9.2 A	2 s

5. CONCLUSION

The inrush current of transformers, sympathetic inrush current analysis, factors that impacting the sympathetic inrush current and energisation of the three transformers are reviewed, as well as a summary of prior works. This paper can assist the researchers in identifying research gaps in this field. Based on the previous research, it can be observed that by comparing with magnetising inrush current, the sympathetic inrush current persists for a longer duration. The novelty of this research is investigating the impact of different energisation techniques on the peak value of sympathetic inrush current when three transformers are connected in parallel. While the previous studies have shown that the sympathetic inrush current occurs when transformers are connected in parallel and this study investigates how controlling the energisation of the transformers can affect the peak value of the sympathetic inrush. Specifically, there are three different energisation conditions are observed in this article which is energised one transformer and switched-on two transformers, energised two transformers and switched-on one transformer and energised three transformers. To conduct this analysis, the peak value of sympathetic inrush current is measured for energised simultaneously and energised at different times. The results show that by energising two transformers and one transformer already in operation is an effective method compared to the other. This strategy not only produces the least amount of current but also uses the fewest number of transformers, thereby maintaining the same operating times. Overall, this research contributes to the existing knowledge on the topic of sympathetic inrush current by exploring the impact of different energisation condition. The results suggest that controlling the number of transformers already switched on and the operating time can significantly reduce the sympathetic inrush current. This research has implications for the design and operation of power systems and can help reduce the risk of equipment damage and power outages caused by sympathetic inrush current. To further mitigate sympathetic inrush current, the article suggests focusing on factors that can affect the current such as system resistance, switching-on angle, load, and power factor. By controlling all of these factors, the sympathetic inrush current can be mitigated and eliminated, failure of equipment can be prevented and power quality can be improved.

ACKNOWLEDGEMENTS

The Ministry of Higher Education Malaysia’s Fundamental Research Grant Scheme (FRGS) with grant number FRGS /1/2020/TK0/UNIMAP/02/15 has generously supported the author. I would sincerely like to thank my supervisor, as well as my entire family and friends, for their unwavering support. To all of them, thank you for your help and blessings in making this effort a success. Thank you so much for everything.

REFERENCES

[1] N. F. Nadhirah, H. A. Halim, N. Hussin, M. Amirruddin, and N. S. M. Noorpi, "Mitigation on sympathetic inrush current phenomena between parallel-connected transformers using PSCAD/EMTDC," in *2022 IEEE International Conference on Power Systems Technology (POWERCON)*, Sep. 2022, pp. 1–6, doi: 10.1109/POWERCON53406.2022.9929634.

[2] S. Sahoo, N. Abeywickrama, T. Bengtsson, and R. Saers, "Understanding the sympathetic inrush phenomenon in the power network using transformer explorer," in *2019 IEEE 4th International Conference on Condition Assessment Techniques in Electrical Systems (CATCON)*, Nov. 2019, pp. 1–5, doi: 10.1109/CATCON47128.2019.CN0031.

[3] S. Liqun, Y. Chenguang, Z. Yuan, and H. Yanhai, "Transformer inrush simulation and analysis," in *2019 IEEE 2nd International Conference on Electronics and Communication Engineering (ICECE)*, 2019, pp. 369–372, doi: 10.1109/ICECE48499.2019.9058576.

[4] A. Moradi and S. M. Madani, "Predictive formulas to improve transformer protection during inrush current using the proposed DC equivalent circuit," *IEEE Transactions on Power Delivery*, vol. 35, no. 2, pp. 919–928, Apr. 2020, doi: 10.1109/TPWRD.2019.2930758.

[5] A. Q. Zhang, T. Y. Ji, M. S. Li, Q. H. Wu, and L. L. Zhang, "An identification method based on mathematical morphology for sympathetic inrush," *IEEE Transactions on Power Delivery*, vol. 33, no. 1, pp. 12–21, Feb. 2018, doi: 10.1109/TPWRD.2016.2590479.

[6] P. N. Papadopoulos, C. G. Kaloudas, T. A. Papadopoulos, G. D. Metaxas, and G. K. Papagiannis, "Magnetizing inrush current effects on large transformer arrangements," in *7th Mediterranean Conference and Exhibition on Power Generation, Transmission, Distribution and Energy Conversion (MedPower 2010)*, 2010, p. 194, doi: 10.1049/cp.2010.0921.

[7] H. A. Halim, "Sympathetic inrush currents in transformer energisation," PhD Thesis, The University of New South Wales, 2018.

[8] P. Elhaminia, A. Moradnouri, and M. Vakilian, "Wind turbine transformer optimum design assuming a 3D wound core," in *2015 30th International Power System Conference (PSC)*, Nov. 2015, pp. 38–44, doi: 10.1109/IPSC.2015.7827724.

[9] G. Jose and R. Chacko, "A review on wind turbine transformers," in *2014 Annual International Conference on Emerging Research Areas: Magnetics, Machines and Drives (AICERA/iCMMD)*, Jul. 2014, pp. 1–7, doi: 10.1109/AICERA.2014.6908172.

[10] L. Cipcigan, W. Xu, and V. Dinavahi, "A new technique to mitigate inrush current caused by transformer energization," in *IEEE Power Engineering Society Summer Meeting*, 2002, vol. 1, pp. 570–574, doi: 10.1109/PESS.2002.1043303.

[11] U. Rudez and R. Mihalic, "A reconstruction of the WAMS-detected transformer sympathetic inrush phenomenon," *IEEE Transactions on Smart Grid*, vol. 9, no. 2, pp. 724–732, Mar. 2018, doi: 10.1109/TSG.2016.2562719.

[12] J. Peng, "Assessment of transformer energisation transients and their impacts on power systems," PhD Thesis, The University of Manchester, Manchester, UK, 2013.

[13] V. Vaddeboina, G. Taylor, and C. Proudfoot, "Switching large transformers on weak transmission networks-real time case study," in *2012 47th International Universities Power Engineering Conference (UPEC)*, Sep. 2012, pp. 1–6, doi: 10.1109/UPEC.2012.6398651.

[14] A.-R. Sedighi and M.-R. Haghifam, "Detection of inrush current in distribution transformer using wavelet transform," *International Journal of Electrical Power and Energy Systems*, vol. 27, no. 5–6, pp. 361–370, Jun. 2005, doi: 10.1016/j.ijepes.2004.12.007.

[15] M. Banerjee and A. Khosla, "Mitigation of magnetising inrush current in three–phase power transformer," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 20, no. 1, pp. 39–45, Oct. 2020, doi: 10.11591/ijeecs.v20.i1.pp39-45.

[16] Y. Wang, S. Li, and X.-Y. Xiao, "Estimation method of voltage sag frequency considering transformer energization," *IEEE Transactions on Power Delivery*, vol. 36, no. 6, pp. 3404–3413, 2021, doi: 10.1109/TPWRD.2020.3041000.

[17] G. B. Kumbhar and S. V Kulkarni, "Analysis of sympathetic inrush phenomena in transformers using coupled field-circuit approach," in *2007 IEEE Power Engineering Society General Meeting*, Jun. 2007, pp. 1–6, doi: 10.1109/PES.2007.386128.

[18] P. Heretik *et al.*, "Research on transformer interaction caused by inrush current and parametric study of this phenomenon," *International Journal of Energy*, vol. 7, no. 3, pp. 72–81, 2013.

[19] P. Pachore, Y. Gupta, S. Anand, S. Sarkar, P. Mathur, and P. K. Singh, "Flux error function based controlled switching method for minimizing inrush current in 3-phase transformer," *IEEE Transactions on Power Delivery*, vol. 36, no. 2, pp. 870–879, Apr. 2021, doi: 10.1109/TPWRD.2020.2995519.

[20] L. Rui *et al.*, "A simulation study of the influence of magnetizing inrush current and sympathetic inrush current of converter transformers," in *2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, 2016, pp. 2282–2286, doi: 10.1109/APPEEC.2016.7779894.

[21] S. Dejun, Y. Xianggen, Z. Zhe, C. Deshu, and Z. Kanjun, "Research on sympathetic interaction between transformers," in *2007 42nd International Universities Power Engineering Conference*, Sep. 2007, pp. 273–276, doi: 10.1109/UPEC.2007.4468959.

[22] T. P. Purohit and P. K. Bhavsar, "Sympathetic Inrush phenomena in parallel and series connected transformers using PSCAD," in *Third International Conference on Emerging Technologies in Engineering, Biomedical, Management and Science*, 2017, pp. 125–130.

[23] A. Zai, "A review on magnetizing inrush current," *International Journal of Advanced Research*, vol. 6, no. 8, pp. 161–165, 2018, doi: 10.21474/IJAR01/7505.

[24] S. S. Dadhe and N. M. Lokhande, "A review on magnetizing inrush current of transformer," *International Journal for Science and Advance Research in Technology (IJSART)*, vol. 3, no. 3, pp. 212–214, 2017.

[25] Y. Fan, Q. Ji, H. Ma, Z. Chen, and K. Shen, "Phenomenon of transformer sympathetic inrush and analysis of an example," *Journal of Physics: Conference Series*, vol. 1486, no. 6, Apr. 2020, doi: 10.1088/1742-6596/1486/6/062039.

[26] A. Farazmand, F. de Leon, K. Zhang, and S. Jazebi, "Analysis, modeling, and simulation of the phase-hop condition in transformers: the largest inrush currents," *IEEE Transactions on Power Delivery*, vol. 29, no. 4, pp. 1918–1926, 2014, doi: 10.1109/TPWRD.2013.2286828.

[27] D. Ahire, "Transformer inrush current mitigation technique," in *2016 Int. Conf. on Automatic Control and Dynamic Optimization Techniques (ICACDOT) International Institute of Information Technology (I^2IT)*, 2016, pp. 543–547.

[28] U. Rudez and R. Mihalic, "Sympathetic inrush current phenomenon with loaded transformers," *Electric Power Systems Research*, vol. 138, pp. 3–10, Sep. 2016, doi: 10.1016/j.epsr.2015.12.011.

[29] V. Barhate, "A review of distinguishing schemes for power transformer's magnetizing inrush and fault currents," *International Journal of Electrical and Electronics Engineering Research*, vol. 3, no. 2, pp. 277–284, 2013.

[30] F. Peng, H. Gao, and Y. Liu, "Transformer sympathetic inrush characteristics and identification based on substation-area information," *IEEE Transactions on Power Delivery*, vol. 33, no. 1, pp. 218–228, Feb. 2018, doi: 10.1109/TPWRD.2017.2730854.

[31] H. A. Halim, B. Phung, and J. Fletcher, "Energising inrush current transients in parallel-connected transformers," in *23rd International Conference and Exhibition on Electricity Distribution*, 2015, pp. 15–18.
[32] S. Du, W. Zhu, and Z. Wang, "Research on principle and countermeasures of the transformer sympathetic inrush," in *2009 Asia-Pacific Power and Energy Engineering Conference*, Mar. 2009, pp. 1–4, doi: 10.1109/APPEEC.2009.4918703.
[33] W. Yangguang, Y. Xianggen, Y. Dahai, and X. Tianqi, "Analysis on the influencing factors of transformer sympathetic inrush current," in *2008 IEEE Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century*, Jul. 2008, pp. 1–8, doi: 10.1109/PES.2008.4596469.
[34] S. P. Patel, "Fundamentals of transformer inrush," in *2011 64th Annual Conference for Protective Relay Engineers*, Apr. 2011, pp. 290–300, doi: 10.1109/CPRE.2011.6035630.

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