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ORIGINAL RESEARCH ARTICLE

# Testing and validation of a modified bride-type nonsuperconducting fault current limiter

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**Abstract**
As the amount of distributed generation (DG) integrated into the distribution network keeps increasing, this leads to an increase in the levels of fault current in the network, and this will result in the network having a fault current above what the existing protecting devices can handle. Hence, an upgrade of protective devices will be necessitated. A lot of techniques have been developed to mitigate against high fault currents. Some of these techniques with their limitations include current-limiting fuses that need constant replacement after an operation; circuit breakers that are very expensive for high current applications; isolation transformers that result in additional network power losses; and current-limiting and air-core reactors that impede the voltage stability of the network. Following these shortcomings, fault current limiters saw the light as the paramount solution to restrain fault currents in the distribution network. This research work is a follow-up of previous research that was on the design of a modified bridge-type nonsuperconducting fault current limiter (MBNSFCL) for application in the distribution network. In this paper, the designed MBNSFCL is tested and validated on two standard IEEE distribution networks, which are the IEEE 13 and the 33 node test networks. The simulation was done using PSCAD/EMTDC. In the case of the IEEE 13 node, the occurrence of a 3 phase to ground fault on the swing bus leads to the source current shooting from an amplitude of 0.602 kA on phase A, 0.335 kA on phase B, and 0.356 kA on phase C to 34.996 kA on phase A, 35.126 kA on phase B, and 34.983 kA on phase C. The fitting of the MBNSFCL into the test network restrains the fault current below the nominal line current, a level at which the circuit breaker can comfortably clear. The virtue of the MBNSFCL is also established when tested on the IEEE 33 node test network. This reveals the reliability of the proposed MBNSFCL for application in the distribution network.

Keywords: Fault current, fault current limiter, distributed generation, nonsuperconducting



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## 1.0 Introduction

Today's power systems are continuing to increase in complexity with the introduction of distributed generation (DG), storage, and electric vehicle charging stations. DGs are rapidly proliferating into the distribution network as a result of the increasing need for sustainable and reliable power supply, in addition to the high cost of building new transmission lines (Hamidi & Chabanloo, 2019). DGs present several advantages to the distribution network as they contribute to decongesting the transmission and the distribution network, reducing network power loss and voltage profile improvement, in addition to most being renewable and hence free from emissions (Sultana et al., 2016). Nevertheless, the integration of DGs in large quantities brings several challenges to the distribution network. One of which is an inherently increased short-circuit fault current. A high fault current is dangerous to the distribution network and operators.

Various techniques have been proposed in the literature to mitigate against fault current in the distribution network. Some of these techniques include the use of current limiting reactors but have the problem of a constant impedance being present in the network during no-fault conditions (Md Shafiul Alam et al., 2018). The current-limiting fuse is a cost-effective and efficient technique that is also used to limit short-circuit fault current in the power system (M. Shafiul et al., 2018). The problem with this method of fault current limiting is the constant replacement of the fuse each time it blows to limit the high short-circuit current (Patil & Thorat, 2017). Isolation transformers have also been proposed to mitigate against fault current but present the problem of being very expensive in addition to the extra power losses they bring into the network (M. Tarafdar, Hagh & Abapour, 2009). Circuit breakers have been a widely used method to resolve fault current problems in the distribution network, but this solution is very expensive when it comes to high current applications and it also requires equipment upgrades (Prigmore & Uzelac, 2019). As a result of these solutions presenting limitations and challenges, researchers proposed fault current limiters (FCLs) as the paramount solution to restrain fault currents without having to upgrade any equipment (Hamidi & Chabanloo, 2019).

Fault current limiters (FCLs) have been revealed to be powerful in restraining fault current in the distribution network to a level clearable by the existing circuit breaker. As per Yamaguchi et al. (1999), a perfect FCL should present the following characteristics:

i. No impedance during no-fault conditions
ii. No power loss.
iii. Low cost
iv. Reliably limiting the desired fault current reliably
v. should rapidly recover after the fault is cleared.



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vi. Automatic and rapid appearance of large enough impedance upon the fault occurrence
vii. Sufficiently large impedance during fault

That notwithstanding, designing such a perfect FCL is an impossibility (Yamaguchi et al., 1999). Several FCLs have been developed over the years, and these can be differentiated based on their underlying technology. These FCLs are solid-state fault current limiters (SSFCL), saturated core fault current limiters (SCFCL), and superconducting fault current limiters (SFCLs) (Arikan & Kucukaydin, 2020). SFCLs are the leading FCLs among existing FCLs, and this is because of their excellent efficiencies in limiting fault current, their fast response, their invisibility to the network during normal network conditions due to their superconducting abilities, and their quick and automatic recovery upon fault clearance (Fedasyuk et al., 2008). According to the material used in their development, SFCLs can be of two types: low-temperature SFCLs and high-temperature SFCLs (Chaudhari & Khampariya, 2016). Also, SFCLs can be classified into inductive SFCL, resistive SFCL, and hybrid SFCL based on their applications (Yadav et al., 2019). Resistive SFCL (RSFCL) are simple and are installed in series with the conductors, and current only flows through them when the current is higher than the critical current expected to flow through the conductor. An Inductive SFCL consists of two saturated iron cores, and a DC base supply is used to operate these two iron cores, which are capable of limiting fault currents in both directions. The hybrid SFCL is a combination of superconductors, semiconductors, fast switches, and circuit breakers or fuses.

Despite SFCLs being excellent at fault current limiting, they are yet to be deployed widely and this is because of the expensive nature of the superconductors used in their fabrication (Mehrdad, Tarafdar, Hagh & Abapour, 2009). Because of this limitation, researchers developed nonsuperconducting fault current limiters (NSFCL) that are similar to SFCLs but use nonsuperconducting coils in place of superconducting coils, making the NSFCL cost-effective and uncomplicated (Abdolkarimzadeh et al., 2017). NSFCL is simple, affordable, and leads to negligible power loss; these have made them suitable alternatives to SFCL (Agheli et al., 2010). There are several NSFCLs and some of them include the series dynamic braking resistor NSFCL that uses a semiconductor switch in parallel with a resistor. The bridge type NSFCL (BNSFCL) comprises two main parts; the shunt branch and the series branch and has been proposed for the enhancement of the fault ride-through of permanent magnet synchronous generators used in wind turbines (Mohammad Shafiul Alam & Yousef, 2018). The modified Bridge Type NSFCL (MBNSFCL) is simply a rearrangement or omission of some of the components of the BNSFCL to obtain an FCL with enhanced qualities compared to the primitive BNSFCL.



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This paper is an extension of a study reported in Fokui et al (2021). In that work, an MBNSFCL was designed for distribution network applications; and it was tested on a simple network that was a single-phase extraction of the IEEE 4 node test distribution network with its inline transformer removed as can be read in (Fokui et al., 2021). In this work, the designed MBNSFCL is tested on the standard IEEE 13 and 33 node test feeders to validate its effectiveness. The rest of this paper is organized thus; the next section is the methodology, and this is followed by results and discussion, and then the conclusion.

## 2.0 Materials and methods

## 2.0 Design Analysis

As explained in Fokui et al. (2021), the designed fault current limiter consists of a diode bridge, a pair of DC reactors, an insulated gate bipolar transistor (IGBT) semiconductor switch, and a command circuit as shown in Fig. 1.

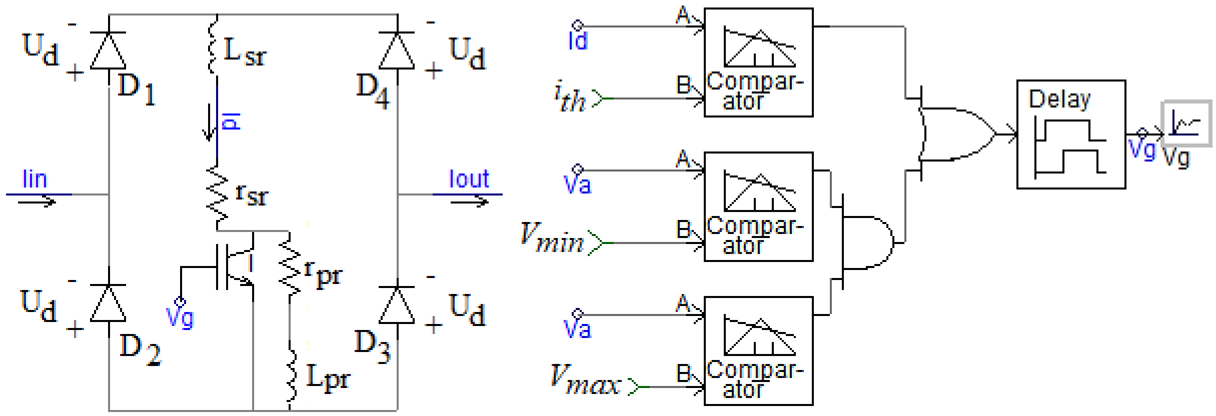


*Fig. 1: Proposed Modified bridge-type nonsuperconducting fault current limiter*

Of the two DC reactors used, one is larger than the other. The larger reactor is the current limiting reactor and it is in parallel with the IGBT. It is slotted into the network by the IGBT to restrain the fault current when a fault arises. The smaller reactor is in series with the IGBT and serves to limit the sudden change in the current flow through the IGBT at the occurrence of the fault. In other words, its main purpose is to protect the IGBT. Both reactors are modeled as a resistor in series with an inductor. A command circuit, as shown in Fig. 1(b), controls the operation of the IGBT. It keeps the IGBT ON when there is no fault in the network and OFF when a fault is detected.



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### 2.1 Operation of the MBNSFCL

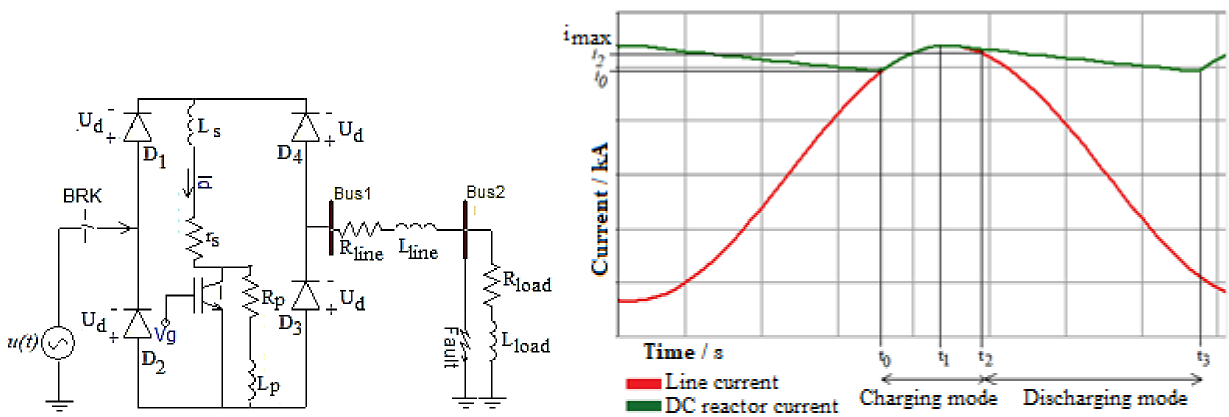
A summary of how the designed MBNSFCL works is as follows;

i. During no fault conditions, the command circuit keeps the IGBT ON. In this state, the current limiting reactor is short-circuited by the conducting IGBT and hence no current flows through it. The series reactor is charged up to the value of the magnitude of the line current. The series reactor fully charged means it now behaves like a shortcircuit and so minimal power is lost through it.

ii. When a fault occurs, the line current becomes greater than the threshold current, and the outcome of this is the turning OFF of the IGBT by the command circuit. This action follows the hasty placement of the current limiting reactor into the network and thus restrains the fault current to wanted levels.

### 2.2 Equations governing the operation of the MBNSFCL

As developed in Fokui et al. (2021), considering the MBNSFCL to be inserted into a sample network as shown in Fig. 2(a), with the reactor and line current waveforms as shown in Fig. 2(b), the key equations governing the operation of the FCL are enlisted in the following subsection.




(a) MBNSFCL inserted into a sample network (b) Reactor and line currents during no-fault conditions

*Fig. 2: Operation of the MBNSFCL inserted into a sample network*

#### 2.2.1 During normal network conditions

a. Series DC Reactor charging mode: When the series DC reactor is charging during the positive cycle of the line current, the line current is expressed as;

$$i_{(t)} = e^{-\left(\frac{R}{L}\right)(t-t_0)}\left[i_0 - \frac{U}{Z}\sin(\omega t_0 - \theta) + \frac{2U_d}{Z}\right] + \frac{U}{Z}\sin(\omega t_0 - \theta) - \frac{2U_d}{R} \quad (1)$$



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$$i_{(t)} = i_{L(t)} = i_{d(t)}$$

*Where:*
*$t_0$ is the time instant during fault when charging mode begins and $i_o$ the current at that time.*

$$L = L_s + L_{line} + L_{load} \quad (2)$$
$$R = r_s + R_{line} + R_{load} \quad (3)$$

The impedance, $Z = \sqrt{R^2 + (L\omega)^2}$, and $\tan\theta = \frac{L\omega}{R}$

b. DC Reactor discharging mode: When the series DC reactor is discharging during the negative cycle of the line current, the line current is expressed as;

$$i_{L(t)} = e^{-\left(\frac{R}{L}\right)(t-t_2)}\left[i_2 - \frac{U}{Z}\sin(\omega t_2 - \theta)\right] + \frac{U}{Z}\sin(\omega t_2 - \theta) \quad (4)$$

*Where:*

$$L = L_{line} + L_{load} \quad (5)$$
$$R = R_{line} + R_{load} \quad (6)$$
$$Z = \sqrt{R^2 + (L\omega)^2},\ \theta = \tan^{-1}\frac{L\omega}{R}, \text{ and } i_2 = i_{2(t)}$$

### 2.2.2 During a fault condition

During a fault condition, the parallel DC reactor is inserted into the network and both the series and parallel DC reactors charge during the positive cycle of the line current and discharge during the negative cycle. During the positive cycle, the line current is expressed as:

$$i_{(t)} = e^{-\left(\frac{R}{L}\right)(t-t_7)}\left[i_7 - \frac{U}{Z}\sin(\omega t_7 - \theta) + \frac{2U_d}{Z}\right] + \frac{U}{Z}\sin(\omega t_7 - \theta) - \frac{2U_d}{R} \quad (7)$$

$$i_{(t)} = i_{L(t)} = i_{d(t)} \text{ and } i_7 = i_{7(t)}$$

*Where:*
$t_7$ is the time instant during fault when charging mode begins and $i_7$ the current at that time.

$$L = L_s + L_{line} + L_p + L_{load} \quad (8)$$
$$R = r_s + R_{line} + R_p + R_{load} \quad (9)$$
$$Z = \sqrt{R^2 + (L\omega)^2} \text{ , and } \theta = \tan^{-1}\left(\frac{L\omega}{R}\right)$$

During the discharging mode of the DC reactors, the discharging current is given by



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$$i_{d(t)} = e^{-\left(\frac{R_d}{L_d}\right)(t-t_9)}\left[i_8 + \frac{2U_d}{R_d}\right] - \frac{2U_d}{R_d} \quad (10)$$

*Where*

$t_9$ is the start of discharging during a fault condition.

$$R_d = r_s + R_p \quad (11)$$

$$L_d = L_s + L_p \quad (12)$$

The inrush current from the source in this mode is expressed as

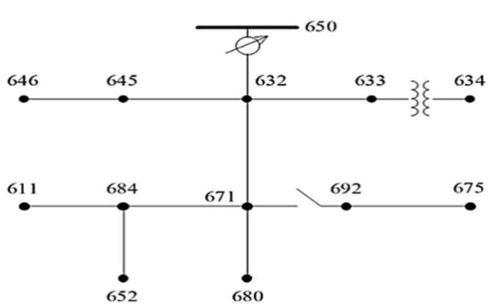
$$i_{L(t)} = e^{-\left(\frac{R}{L}\right)(t-t_9)}\left[i_9 - \frac{U}{Z}\sin(\omega t_9 - \theta)\right] + \frac{U}{Z}\sin(\omega t_9 - \theta) \quad (13)$$

Where

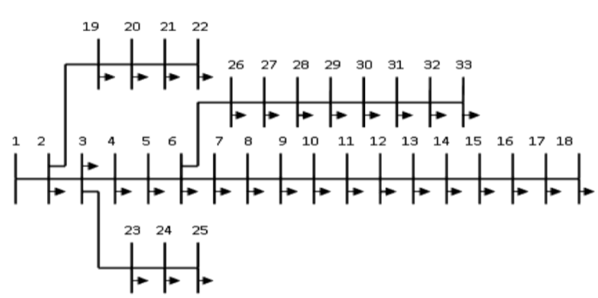
$Z = \sqrt{R^2 + (L\omega)^2}$, $\theta = \tan^{-1}\frac{L\omega}{R}$, $i_9 = i_{9(t)}$

## 2.3 Test Networks

To check and confirm the virtue of the designed modified bridge-type NSFCL in limiting fault current in the distribution network, two test networks are used; the IEEE 13-node and the IEEE 33-node test feeders. The IEEE test distribution networks are well-known distribution networks that provide a common set of data to be utilized by program developers and users to validate the effectiveness of their solutions (Kerting, 1991). The IEEE 13-node feeder network is a very small but heavily loaded distribution network at a three-phase voltage of 4.16 kV, and it comprises both overhead and underground lines with a variety of phasing (Kersting, 2000). The IEEE 33-node test feeder, on the other hand, is a three-phase balanced network at a voltage of 12.66 kV. Fig. 3 shows the single-line diagram of both networks.




(a) IEEE 13 node test feeder




(b) IEEE 33 node test feeder

*Fig. 3: IEEE Test networks*



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### 2.4 Simulation parameters

The simulation parameters to test and validate the MBNSFCL are shown in Table 1. The values for the various components of the NSFCL are shown for each network guided by the equations developed by Fokui et al. (2021) governing the functional principles of the FCL. The series reactor in each network is chosen to be as small as possible such that minimal current ripples are experienced in the MBNSFCL during no fault conditions. These are also guided based on the smallest values of resistors and inductors available on the market. The current limiting reactor is chosen such that the current flow during a fault is safe enough for the circuit breaker in each network to clear conveniently. PSCAD/EMTDC is used to simulate and validate the effectiveness of the MBNSFCL. PSCAD/EMTDC is used to simulate and validate the effectiveness of the MBNSFCL.

*Table 1: Simulation parameters for the NSFCL in each study network*

| | Case Networks | |
|---|---|---|
| | IEEE 13 | IEEE 33 |
| Fault ON resistance | $R_f = 0.001$ ohm | $R_f = 0.001$ ohm |
| NSFCL Power circuit | $L_{sr} = 0.001$H<br>$r_{sr} = 0.003$ ohm<br>$L_{pr} = 0.05$H<br>$R_{pr} = 4$ ohm<br>$U_d = 1$V | $L_{sr} = 0.01$H<br>$r_{sr} = 0.03$ ohm<br>$L_{pr} = 0.1$H<br>$R_{pr} = 30$ ohm<br>$U_d = 1$V |
| NSFCL Command | $i_{dth} = 1.25$kA<br>$V_{max} = 2.74$V<br>$V_{min} = 2.7$V | $i_{dth} = 0.42$kA<br>$V_{max} = 10.4$V<br>$V_{min} = 10.0$V |

### 3.0 Results and discussion

The designed fault current limiter is tested on the IEEE 13 and 33 node test feeders. The simulation was done using PSCAD/EMTDC. The simulation settings are; a runtime of 1 second, a 3-phase to ground fault occurs at 0.5 second, the circuit breaker clears the fault at 0.54 seconds, and the network is restored at 0.6 seconds. The results obtained from the simulations are:

### 3.1 The NSFCL Inserted into the IEEE 13 Node Test Network

The proposed MBNSFCL is tested in the IEEE 13 node test network and the results are;

#### 3.1.1 Fault current limiting

Without the MBNSFCL, the generator current during normal network conditions, during the 3-phase to ground fault (3Ph-G), when the fault is cleared, and when the network is restored is



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shown in Fig. 4. It is observed that the 3Ph-G fault applied on the swing bus leads to the amplitude of the source current to escalate from 0.602 kA in phase A, 0.335 kA in phase B, and 0.356 kA in phase C during no-fault condition network conditions as shown in Fig. 5 to 34.996 kA in phase A, 35.126 kA in phase B, and 34.983 kA in phase C as shown in Fig. 6 when the MBNSFCL is absent in the network.

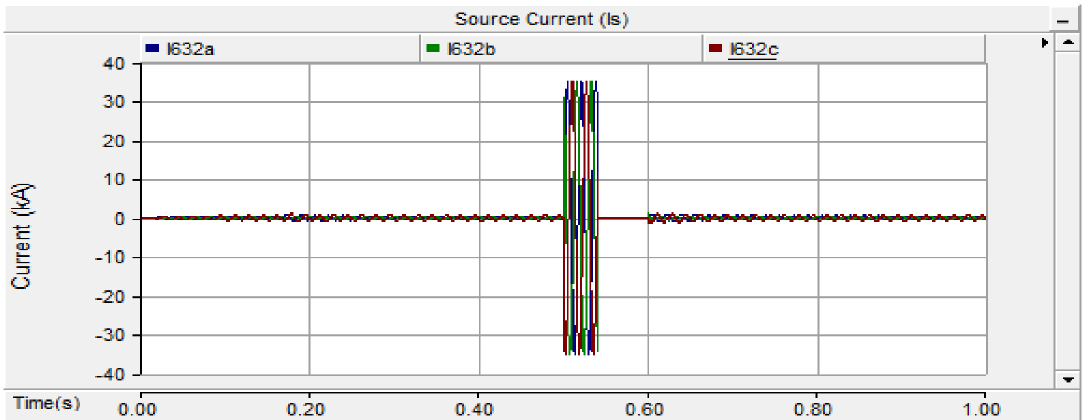


*Fig. 4. The current waveform of the IEEE 13 node test network when 3Ph-G fault was applied on its swing bus (No MBNSFCL)*

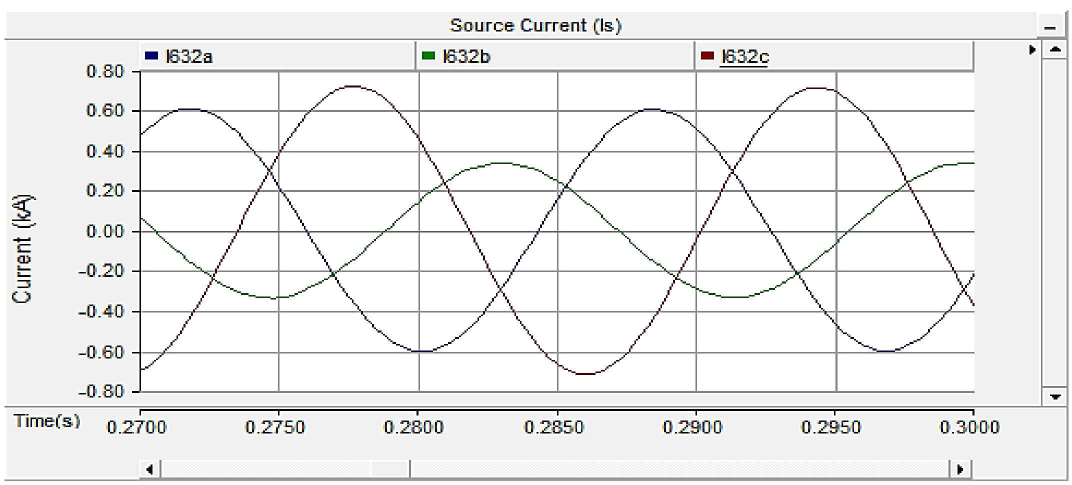


*Fig. 5. The current waveform of the source during normal network conditions (No MBNSFCL)*



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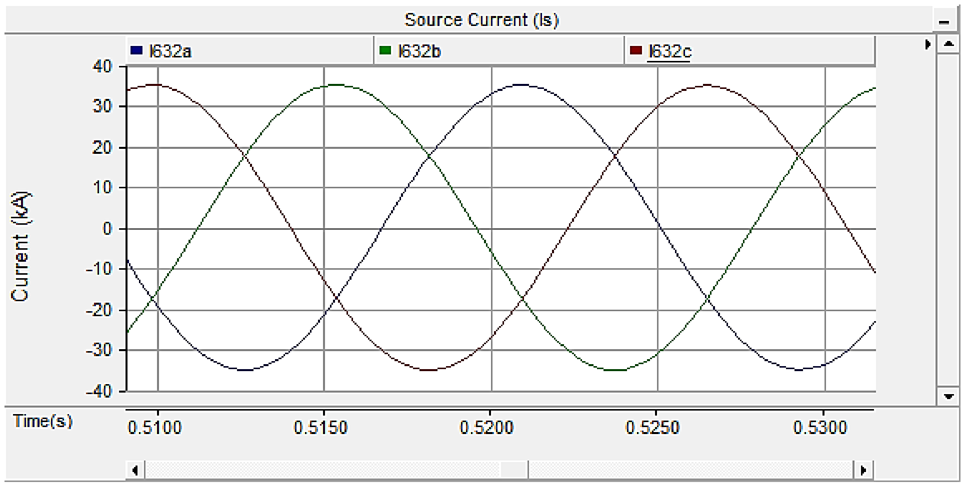


*Fig. 6. The current waveform of the source during fault conditions (No MBNSFCL)*

With the proposed MBNSFCL inserted into every phase of the network, the fault current is efficiently suppressed to nominal margins, as can be seen in Fig. 7. The MBNSFCL restrains the fault current to a level suitable for the circuit breaker to clear. A clear observation of the line current during a no-fault condition when the MBNSFCL is used reveals no difference from that when the MBNSFCL is absent. This, therefore, means that the MBNSFCL does not affect the line current waveform during normal network conditions and, in so doing, results in minimal extra power losses due to its presence in the network.

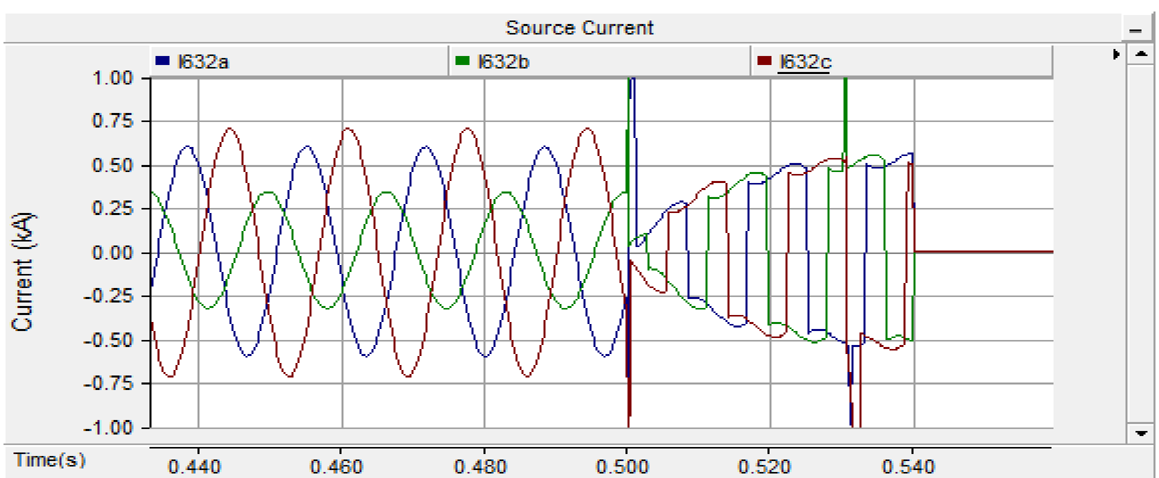


*Fig. 7. Limitation of fault current by the MBNSFCL at the occurrence of the fault at 0.5second*



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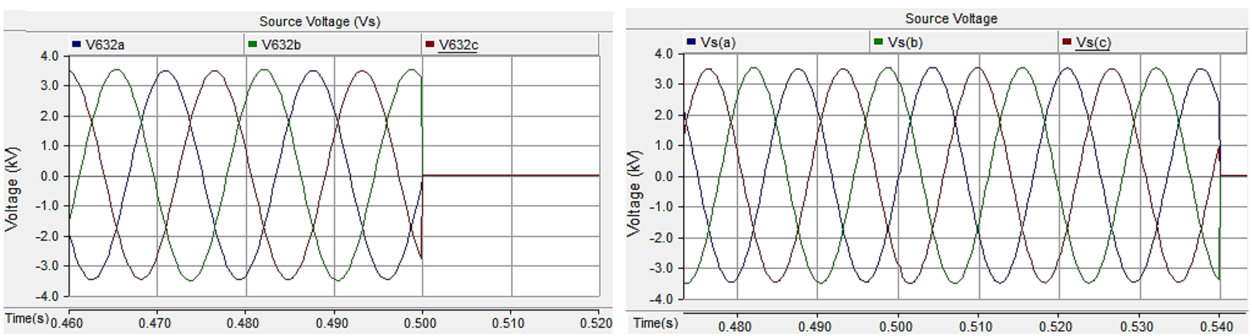
### 3.1.2 Substation voltage

The effect of the designed MBNSFCL on the network's source voltage is analyzed, and it is noticed that the substation voltage during no-fault conditions (before 0.5 second) when the MBNSFCL is not used and when it is used is the same as seen in Fig. 8. When the MBNSFCL is not present in the network, the occurrence of the fault at 0.5 second causes the substation to stop supplying and, as a result, its voltage to fall to zero, as shown in Fig. 8(a). With the MBNSFCL present in the network, the fault at 0.5 seconds does not prevent the substation from continuing to supply its constant voltage, as shown in Fig. 8(b). This shows that the designed MBNSFCL can effectively be used for fault ride-through applications as it will keep the source voltage constant until the fault is removed or cleared. Fault ride-through is important for distributed generation technologies to avoid a short circuit at a higher voltage that leads to widespread generation losses.




(a) Without the MBNSFCL (b) With the MBNSFCL

*Fig. 8: The voltage waveform of the source without and with the designed MBNSFCL*

### 3.1.3 Load voltage and current

To validate the invisibility of the proposed MBNSFCL in the network during the no-fault condition, the voltage and current waveforms of the loads are looked into critically. It is observed that the waveforms of the loads' current and voltage are not affected by the presence of the MBNSFCL during normal network conditions, as can be seen with the current and voltage waveforms of load node 671 shown in Fig. 9 and Fig. 10.



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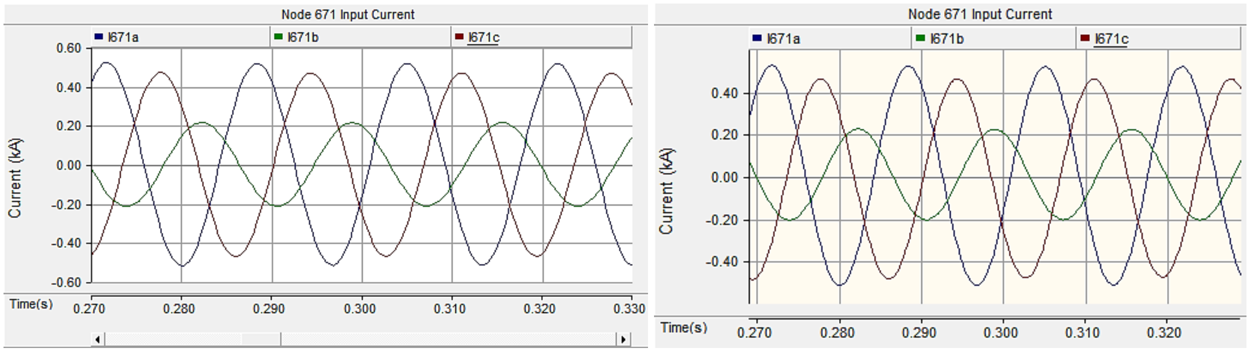
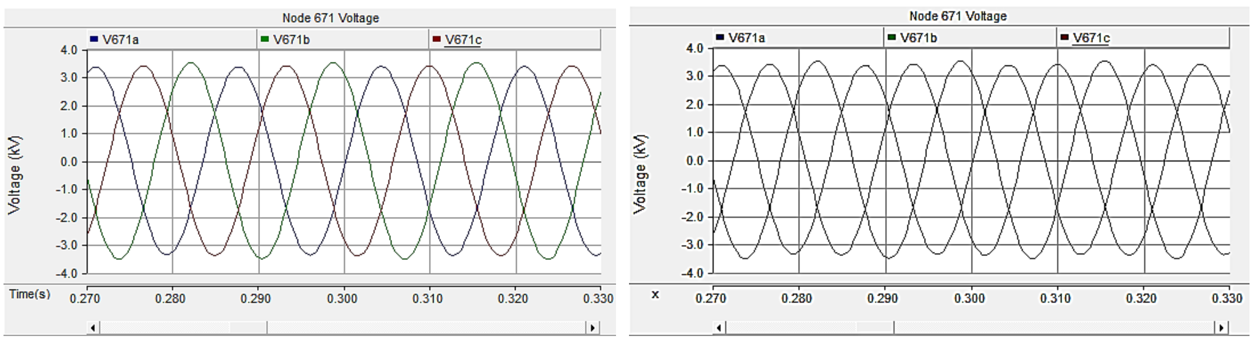



(a) Without MBNSFCL (b) With MBNSFCL

*Fig. 9. No impact of the MBNSFCL on the load current of node 671 during normal conditions*




(a) Without MBNSFCL (b)With MBNSFCL

*Fig. 10. No impact of the MBNSFCL on the load voltage of node 671 during normal conditions*

### 3.2 MBNSFCL Inserted into the IEEE 33 Node Test Network

Testing the designed modified bridge nonsuperconducting fault current limiter in the IEEE 33 node test network also yields satisfactory results, as shown in this section.

#### 3.2.1 Fault current limiting

The current waveform of the source during normal conditions, fault, fault cleared and network restored when the MBNSFCL is not used is shown in Fig. 11. It is seen that the amplitude of the current drops from 0.2078 kA during normal conditions to 2.47 kA when the 3Ph-G fault occurs. This large fault current is successfully minimized to a convenient level when the NSFCL is brought into the network, as can be seen in Fig. 12. It can also be observed that the line current during no-fault conditions when the MBNSFCL is used is not altered by the FCL, just as in the case of the IEEE 13-node test network.



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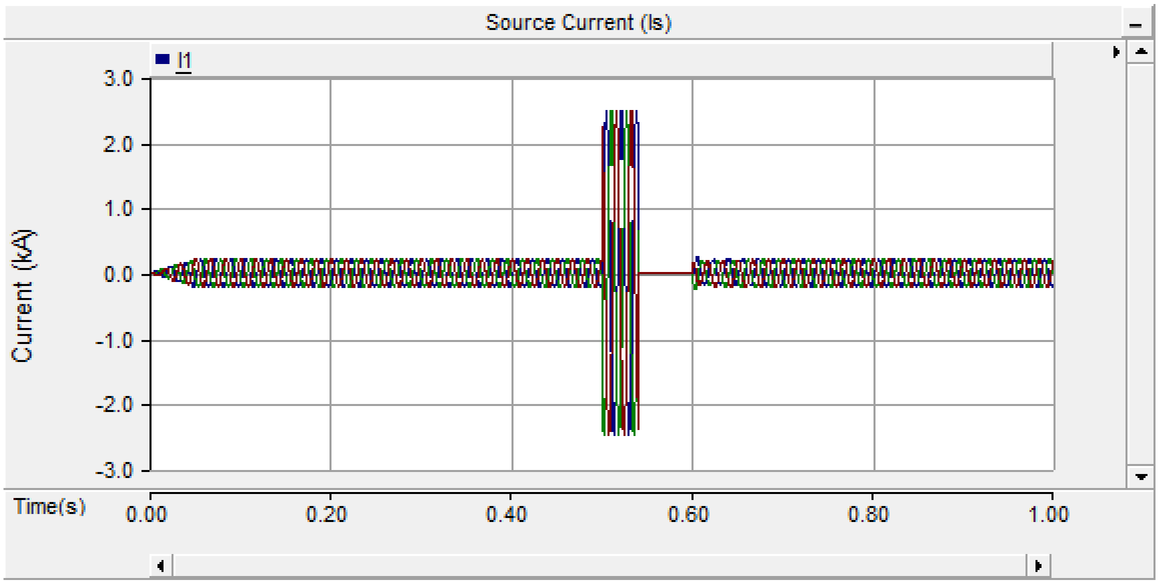


*Fig. 11: The current waveform of the source without the MBNSFCL*

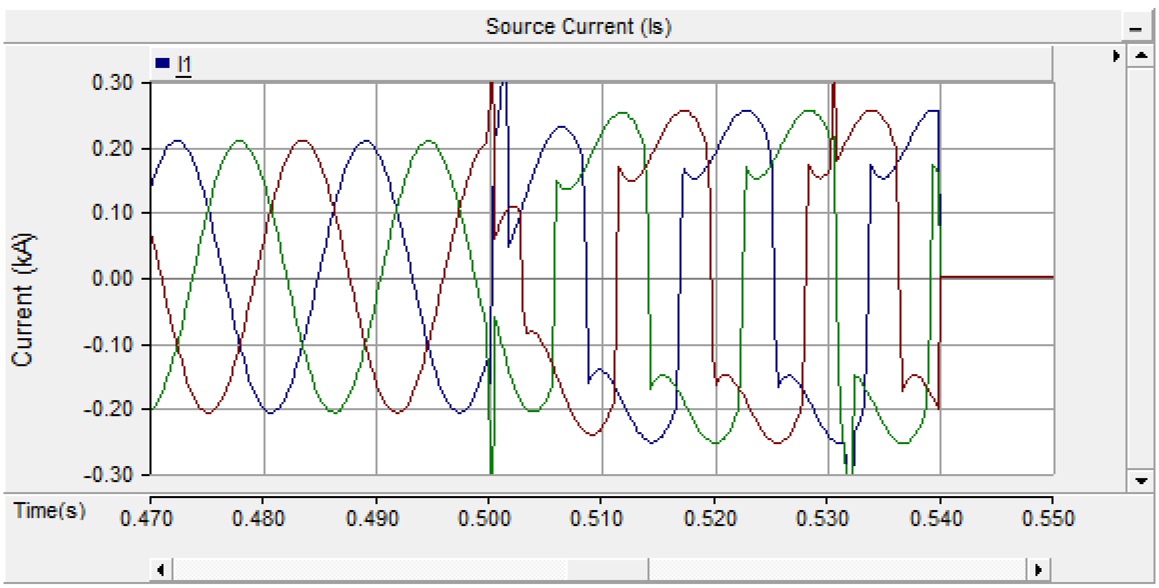


*Fig. 12: The current waveform of the source with the MBNSFCL*

### 3.2.2 Impact of the proposed MBNSFCL on the source voltage

Just like in the case of the IEEE 13 node test feeder, the MBNSFCL does not have an impact on the source voltage waveform during no-fault conditions, as can be seen in Fig. 13.



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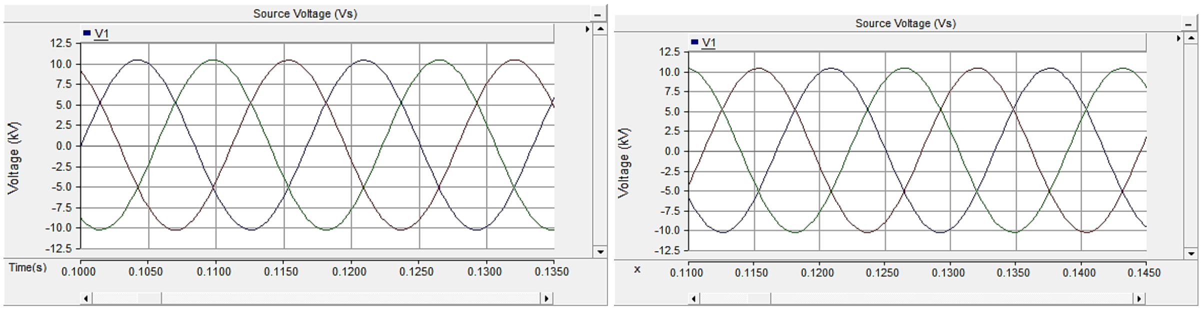
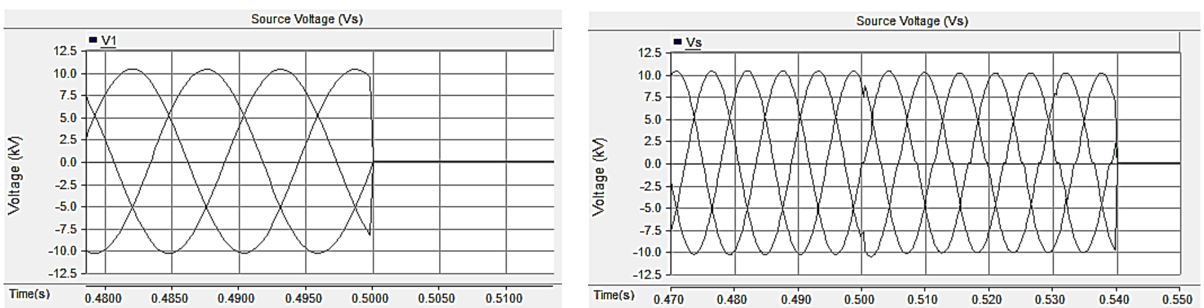



(a) Without MBNSFCL (b) With MBNSFCL

*Fig. 13. The voltage waveform of the source is not affected by the proposed MBNSFCL*

When the MBNSFCL is not used during the 3Ph-G fault, the source voltage is pulled down to zero, as shown in Fig. 14(a). Fig. 14(b) shows that when the MBNSFCL is used, the source waveform is maintained until the fault is cleared by the circuit breaker at 0.54 seconds. This demonstrates the effectiveness of the designed NSFCL in fault ride through enhancement.




(a) Without MBNSFCL (b) With MBNSFCL

*Fig. 14: Effectiveness of the proposed MBNSFCL for voltage ride-through*

### 3.2.3 Impact of the MBNSFCL on the load current and voltages

As can be seen in Fig. 15 and Fig. 16, the MBNSFCL does not have any effect on the load current and voltages during no-fault conditions. This again shows that the MBNSFCL is invisible to the network during no-fault conditions and only appears when a fault occurs.



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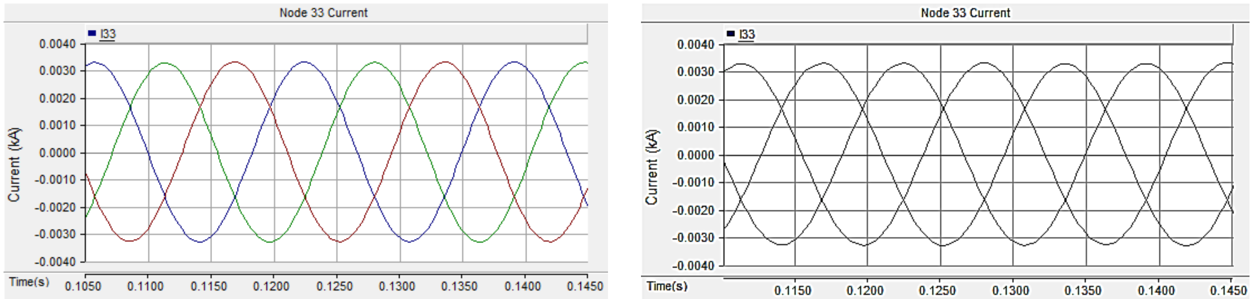
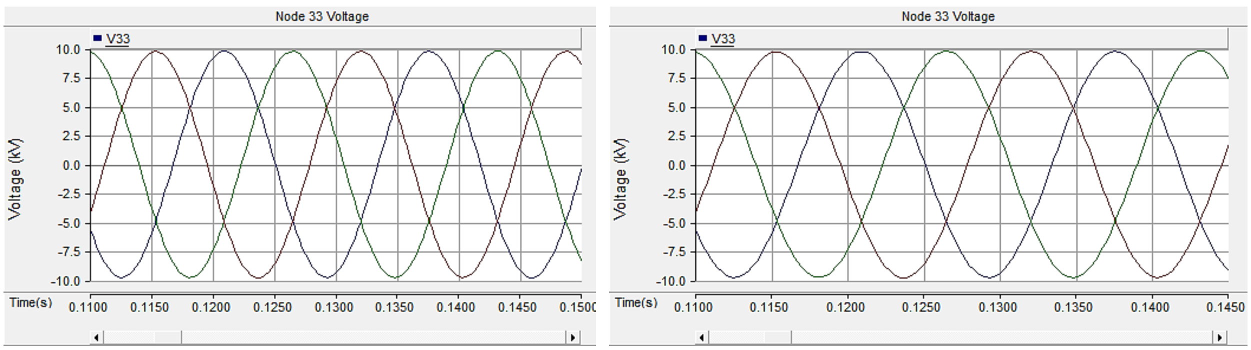



(a) Without MBNSFCL (b) With MBNSFCL

*Fig. 15: The proposed NSFCL does not affect load current during normal conditions*




(a) Without MBNSFCL (b) With MBNSFCL

*Fig. 16: Proposed NSFCL does not affect load voltage during normal conditions*

## 4.0 Conclusion

The paper is an extension of Fokul et al. (2021). In the work, a modified bridge-type nonsuperconducting fault current limiter (MBNSFCL) was designed for distribution network applications and was tested on a simple network that was a single-phase extraction of the IEEE 4 node test distribution network with its inline transformer removed. In this present study, the testing of the MBNSFCL was done on two well-known test distribution networks, which are the IEEE 13 node test feeder, which is a short, heavily loaded, and unbalanced network, and the IEEE 33 node test feeder, which is a large and balanced network. The simulation was done using PSCAD/EMTDC. Simulation results for both networks demonstrated the effectiveness of the network in limiting the line current on each phase of the network to desired values convenient for the main circuit breaker to clear. This, therefore, means that the proposed MBNSFCL can be integrated into today's distribution network with an increasing number of PVs that may lead to an increase in fault current levels without the necessity to upgrade the network's protective equipment. It is also observed that the MBNSFCL in both networks does not affect the network's parameters during no fault conditions. That is the source voltage and current, and the loads'



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voltage and current waveforms remain unaltered during normal network conditions when the MSNSFCL is used. This shows that minimal additional network losses are incurred due to the designed MBNSFCL present in the network. This work demonstrates that this designed MBNSFCL is an all-in-one solution to limit fault current in the distribution, enhance fault-ride through capabilities, improve power quality, compensate for voltage sags, and avoid the high cost of upgrading or replacing the distribution network protective equipment to accommodate a large number of DGs and storage.

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### 5.2 Analysis and Research

The analysis and research were conducted in the Department of Electrical Engineering, at the Pan African University Institute for Basic Sciences, Technology and Innovation, hosted at Jomo Kenyatta University of Agriculture and Technology.

### 5.3 Presentation of the study, findings, and a portion of the work

These preliminary findings were presented in abstract communication and oral presentation at the 16th JKUAT scientific, technological, and industrialization conference held at Jomo Kenyatta University of agriculture and technology, Kenya, from March 24 to 25, 2022. This paper's abstract may be found at: https://drive.google.com/file/d/1pCiWvu_euU7VfS-_Q4krXYViWSeFelml/view from the 16th JKUAT and 1st Hybrid Scientific Conference.

### 5.4 Declaration of interest

All authors declare that they have no conflict of interest. The authors retain the copyright of this work.

This paper's opinions, assessments, knowledge, and conclusions are exclusively the authors' and they are responsible for the content, editing decisions, manuscript composition, viewpoints expressed, acceptance of the final content, and consent to publish if any errors remain. The manuscript studies were organized in a chosen manner based on their relevance to the subject matter and predicted work quality, rather than being exhaustive in fulfillment of the requirements for obtaining the degree "Ph.D. in Electrical Engineering (Power Systems Option)."



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