Fuse-Fuse Protection Scheme ETAP Model for IEEE 13 Node Radial Test Distribution Feeder

Kemei Peter Kirui, David K. Murage, and Peter K Kihato

Abstract—According to NEC 240.101 regulations each and every component of a power system distribution network has to have an over-current protective device (OCPD) for its protection. The OCPDs must coordinate with other devices both upstream and downstream for a reliable operation and protection of the power systems distribution network. There are four equipment/components for the IEEE 13 node radial test feeder each modelled in this paper to be protected by fuses. These components are namely the nodes, the underground cables, the overhead distribution lines and the transformers. Equipment protection is an important and necessary exercise of performing power systems protection coordination processes. The equipment and their over-current protective device’s time-current characteristic (TCC) curves are important tools used to show and to indicate the protection requirements, landmark points and damage curves for all power systems equipment. Individual equipment protection requirements and limitations are described and identified by use of their various landmarks and damage curves. These damage curves and the landmark points are all superimposed with the Time-Current Characteristic curves of the Over-Current Protective Devices used in protecting the equipment on one composite TCC graph. Equipment damage curves which fall to the right and above the Over-Current Protective Device’s TCC curves with sufficient margins are considered to be protected by the OCPDs. Equipment damage curves which fall to the left and below the OCPD’s TCC curves are considered not to be protected by the OCPDs. IEEE Standard 241 states that on all power systems, the OCPDs should be selected and set to open before the Ampacity mark, the short circuit damage curves, and both the thermal and the mechanical damage curve limits of the protected components are exceeded. This paper presents a detailed Fuse-Fuse protection scheme for the IEEE 13 node radial test feeder as modeled on the Electrical Transients Analysis Program (ETAP).

Index Terms—Transformer Magnetizing In-rush Points, Transformer Thermal Damage Curves, Transformer Mechanical Damage Curves, Transformer Full Load Ampere Mark, Conductor Intermediate Thermal Overload Limit Curves, Conductor Short Circuit Damage Curves, Fuse TCC Curves, Equipment TCC Curves.

I. DISTRIBUTION EQUIPMENT PROTECTION REQUIREMENTS

In order to effectively protect a power systems distribution network and implement the fuse-fuse protection scheme, NEC article 240-101 states that “Feeders Rated Over 1000V must have Over Current Protection Provided either by a Fuse rated not more than 300 Percent of the Feeder Ampacity or by a Circuit Breaker with a Long Time Trip Element Set not more than 600% of the Feeder Ampacity” [1]. These OCPDs must clear the faults prior to reaching the withstand capability of the equipment to be protected. Therefore, the OCPDs must be set to provide over-current protection as per the NEC 240.101 requirements and also to provide overload withstand protection as per ANSI/IEEE regulations [2]. The NEC 240.101 requirements states that:

- The ratings of a fuse used to protect an underground cable electrical conductor should not be more than 100% of the cables’ ampacity. [2].
- The ratings of a fuse used to protect an overhead electrical conductor should not be more than 300% of the electrical conductor’s ampacity. [2].

Transformer protective devices must be set within the NEC 450.3 requirements for transformer overload protection to allow the normal magnetizing inrush currents to flow [3]. The transformer primary side protective devices must not operate for the normal magnetizing inrush currents that occur when energizing the transformer [3]. The magnetizing inrush points are established at 8 times the transformer full load current (FLA) for a period of 0.1 seconds for transformers under 2500kVA and for transformers above 2500kVA the inrush point is at 10 or 12 times the transformer FLA for a period of 0.1 seconds [4][5]. The transformer protection coordination constraints are [5]:

- Transformers having percentage impedance less than 10% the primary/source side protection must have an upstream fuse rated at 300% of the transformer full load currents.
- Transformers rated over 1000V on the secondary/load side and having percentage impedance less than 6% the load side protection must have a downstream fuse rated at 250% of the transformer full load currents.
- Transformers rated over 1000V on the secondary/load side and having percentage impedance between 6% – 10% the load side protection must have a downstream fuse rated at 225% of the transformer full load currents.
- Transformers rated less than 1000V on the secondary/load side and having percentage impedance less than 10% the load side protection must have a downstream fuse rated at 125% of the transformer full load currents.

Published on September 29, 2019
Kemei P. Kirui is with the Department of Electrical and Electronic Engineering, JKUAT, Kenya. (e-mail: kemei.kirui@gmail.com)
David K. Murage is with the Department of Electrical and Electronic Engineering, JKUAT, Kenya. (e-mail: dkmurage25@yahoo.com)
Peter K Kihato is with the Department of Electrical and Electronic Engineering, JKUAT, Kenya. (e-mail: pkihato@jkuat.ac.ke)

DOI: http://dx.doi.org/10.24018/ejers.2019.4.9.1549
II. EQUIPMENT PROTECTION REQUIREMENTS, LANDMARKS AND DAMAGE CURVES

A. Transformer Protection Requirements.

Even though transformers are the simplest and most reliable devices in an electrical power system, transformer failures can occur due to internal or external conditions that make the transformer incapable of performing its proper functions. Appropriate transformer protection should be used with the objectives of protecting the electrical power system in case of a transformer failure and also to protect the transformer itself from the power system disturbances like the faults.

1) The Transformer Full Load Ampere (FLA)

The full load ampere (FLA) is the rated continuous current carrying capacity of a transformer at a referenced ambient temperature and allowable temperature rise. The FLA mark is located on the transformer TCC log-log graph at the top decade at the 1000 seconds mark as seen from Fig 1. [6].

2) The Transformer Through-Fault Damage Curves

Transformer through-fault damage curves are plotted at the top three decades of the transformer TCC log-log graph from the 2 seconds mark to the 1000 seconds mark. The transformer through fault damage curves are both the thermal and mechanical damage curves as seen from Fig 1. [6].

3) The Transformer Magnetizing Inrush Current Point(s)

One or more transformer magnetizing inrush current points may be plotted on a TCC for a power transformer. These magnetizing inrush currents points are expressed in peak amperes with the most common point being at 8 or 12 times the rated FLA at 0.1 seconds mark and at 25 times of the rated FLA at 0.01 seconds mark. [6].

4) Transformer Protection Settings (From Fig 2)

Step 1: Identify the Transformer TCC Curve Landmarks
- The Full Load Ampere point which is located at the upper decade at the 1000seconds mark.
- The Thermal Damage Curve which is located in the upper 3 decades starting at the 2 seconds mark to the 1000seconds mark.
- The Mechanical Damage Curve which is located in the middle decade between the 2 seconds mark and the 4 seconds mark.
- The magnetizing inrush point defined at 8 or 12 times the FLA located at the 0.1 seconds mark and at 25 times of the FLA mark located at the 0.01 seconds mark.

Step 2: Identify from the TCC Curves the Transformer Operating Area
- The transformer operating area is located to the left and below the full load ampere mark and also to the left and below the transformer magnetizing inrush points.
- The transformer damage area is located to the right and above the through-fault damage curves both the thermal damage curve and the mechanical damage curve.

Step 3: Size and Set the Over-Current Protective Devices

- Set the protective device’s TCC Curves above the transformer full load ampere mark and also above the transformer magnetizing inrush points. [7].
- Set the protective device’s TCC Curves below both the transformer thermal and mechanical through-fault damage curves.

B. Overhead Lines/Underground Cables Conductor Protection Requirements.

1) The Overhead Transmission Lines/Underground Cables Conductor Ampacity

The ampacity is the rated continuous current carrying capacity of a conductor at a referenced ambient temperature and allowable temperature rise. If a conductor is loaded continuously above its rated ampacity the insulation temperature design limits will be exceeded. This will lead to loss of conductor life and not instantaneous failure. The electrical conductor ampacity landmark is located at the top decade of the TCC curve of the conductor material at the 1000 seconds mark as seen from Fig 3. [6].


The intermediate thermal overload limit curves of an electrical conductor are the over-current operating limits that

DOI: http://dx.doi.org/10.24018/ejers.2019.4.9.1549
if exceeded will damage the insulation of an insulated power conductor. Intermediate thermal overload limit curves are based on the thermal inertia of the conductor, the insulation and the surrounding material. The electrical conductor intermediate overload limit curve is located at the upper 2 decades of its TCC Curves starting from the 10 seconds mark to the 1000seconds mark as seen from Fig 3. [6].

3) Overhead Lines/Underground Cables Conductor Short Circuit Damage Curve.

This is the ampere limit that if exceeded will damage the bare aerial conductor or the insulation of an insulated power conductor. Short circuit damage curve is plotted in the lower three decades of the conductor TCC curve starting at the 0.01 seconds mark to the 10 seconds mark as seen from Fig 3. [6].

4) Overhead Lines/Underground Cables Conductor Protection Settings. (From Fig 4)

Step 1: Identify the Conductor Protection Landmarks
- The conductor ampacity mark which is located in the upper decade at the 1000 seconds mark
- The conductor intermediate thermal overload limit curve which is located in the upper two decades (typically not shown) starting at the 10 seconds mark to the 1000 seconds mark
- The conductor short circuit damage curve which is located at the bottom three decades between the 0.01 seconds mark and 10 seconds mark.

Step 2: Identify from the Protection Landmarks the Conductor Operating Area
- The conductor operating area is located to the left and below the ampacity mark
- The conductor damage area is located to the right and above the intermediate thermal overload limit curve and also the short circuit damage curve.

Step 3: Size and Set the Over-Current Protective Devices
- Set the protective device’s TCC curves to pick-up at or below the ampacity mark, conductor intermediate thermal overload limit curve and the conductor short circuit damage curve. [8].

III. IEEE 13 NODE RADIAL TEST FEEDER FUSE-FUSE PROTECTION SCHEME ETAP MODEL REQUIREMENTS

A. IEEE 13 Node Radial Test Feeder One –Line Diagram

The IEEE 13 node radial test feeder is a short, unbalanced and relatively highly loaded 4.16kV feeder. The features of the IEEE 13 node radial test feeder is basically the presence of: A 5000kVA 115kV/4.16kV Delta/Star substation transformer connected to the swing/grid node; One substation voltage regulator consisting of three single phase units connected in star; Eight overhead distribution lines and two underground cables with variety of lengths and phasing; Unbalanced delta and star connected distributed and spot loads; Two shunt capacitor banks one having a single phase
IEEE 13 node radial test feeder was modeled using ETAP electrical simulation software. A one-line diagram was drawn for the feeder and fuses modeled as both the upstream and downstream OCPDs for protecting the radial test feeder as shown in Fig 7. A protection scheme utilizing a total of 23 fuses was modeled for the feeder protection. Each component on the feeder had a fuse as its downstream OCPD with the fuse generally referred to as the load fuse. An upstream fuse was also modeled and set to coordinate with the downstream fuse for the feeder protection. The fuse’s current ratings, voltage limits and TCC curves were carefully selected so that we achieve a selectively coordinated Fuse-Fuse protection scheme for the feeder.

![Fig. 6: IEEE 13 Node Radial Test Feeder Schematic Diagram](image)

IEEE 13 node radial test feeder was modeled using ETAP electrical simulation software. A one-line diagram was drawn for the feeder and fuses modeled as both the upstream and downstream OCPDs for protecting the radial test feeder as shown in Fig 7. A protection scheme utilizing a total of 23 fuses was modeled for the feeder protection. Each component on the feeder had a fuse as its downstream OCPD with the fuse generally referred to as the load fuse. An upstream fuse was also modeled and set to coordinate with the downstream fuse for the feeder protection. The fuse’s current ratings, voltage limits and TCC curves were carefully selected so that we achieve a selectively coordinated Fuse-Fuse protection scheme for the feeder.

![Fig. 7: IEEE 13 Node Radial Test Feeder Fuse Protection Scheme One-Line Diagram](image)

### B. Overhead Lines Primary Protection Requirements, Ampacity Mark, Damage Curves and Protective Devices Curves

All the overhead distribution lines segments were given specific identification names with the codes chosen with reference to the node points the lines have been connected in between. Each fuse was given a unique identification code based on the line segment reference it is protecting. The upstream fuse was given a code describing the two node points between which the distribution line has been connected on to and the downstream fuse was given a code based on the node the line has been terminated at. Table 1 gives the identification codes for all the fuses used to protect the eight overhead distribution lines. Every overhead line was protected by two fuses one connected at the source node referred to as the upstream fuse and the other connected at the load node and referred to as the downstream fuse.

<table>
<thead>
<tr>
<th>Line Segment</th>
<th>Source Node</th>
<th>Load Node</th>
<th>Upstream Fuse</th>
<th>Downstream Fuse</th>
</tr>
</thead>
<tbody>
<tr>
<td>LINE632-645</td>
<td>632</td>
<td>645</td>
<td>F632-645</td>
<td>F645</td>
</tr>
<tr>
<td>LINE632-633</td>
<td>632</td>
<td>633</td>
<td>F632-633</td>
<td>F633</td>
</tr>
<tr>
<td>LINE645-646</td>
<td>645</td>
<td>646</td>
<td>F645-646</td>
<td>F646</td>
</tr>
<tr>
<td>LINE650-632</td>
<td>650</td>
<td>632</td>
<td>F650-632</td>
<td>F632</td>
</tr>
<tr>
<td>LINE632-671</td>
<td>632</td>
<td>671</td>
<td>F632-671</td>
<td>F671</td>
</tr>
<tr>
<td>LINE671-684</td>
<td>671</td>
<td>684</td>
<td>F671-684</td>
<td>F684</td>
</tr>
<tr>
<td>LINE671-680</td>
<td>671</td>
<td>680</td>
<td>F671-680</td>
<td>F680</td>
</tr>
<tr>
<td>LINE684-611</td>
<td>684</td>
<td>611</td>
<td>F684-611</td>
<td>F611</td>
</tr>
</tbody>
</table>

1) **LINE632-633 Protection Requirements, Ampacity Mark and Damage Curves**

It is an overhead three phase distribution line connecting the branch segment between node 632 and node 633. The line phase conductors have ampacities of 340/Ampères and are each protected by two fuses. The upstream fuse is F632-633 and the downstream fuse is F633. The TCC Curve for the overhead phase conductors and its protective fuses is shown in Fig 8. The TCC curve shows the conductor ampacity of 340A located at the upper decade at the 1000 seconds mark of the TCC curve and the conductor short circuit damage curve located at the bottom three decades starting from the 0.01 seconds mark to the 10seconds mark. From the TCC curve, the fuse’s TCC trip curves are both below and to the left of the line’s ampacity mark, its intermediate thermal overload limit curve and its short circuit damage curve hence the overhead line is well protected by the fuses. Fuse F632-633 has a continuous current rating of 250A and is within the NEC 240.101 maximum limit of the line conductor’s 300% ampacity of 1020A. Fuse F633 also has a continuous current rating of 150A which is within the NEC 240.101 maximum limit of the overhead line conductor’s 300% ampacity of 1020A.

![Fig. 8: LINE632-633 Ampacity Mark, Short Circuit Damage Curve and Fuses F632-633 and F633 Trip Curves](image)

2) **LINE632-645 Protection Requirements, Ampacity Mark and Damage Curves**

This is an overhead three phase distribution line

DOI: [http://dx.doi.org/10.24018/ejers.2019.4.9.1549](http://dx.doi.org/10.24018/ejers.2019.4.9.1549)
connecting the branch segment between node 632 and node 645. The line phase conductors have ampacities of 340\text{Ampere}s and are each protected by two fuses. The upstream protective device is fuse F632-645 and the downstream protective device is fuse F645. The TCC Curve for the overhead distribution line phase conductor and its protective fuses is shown in Fig 9. The TCC curve shows the overhead conductor ampacity of 340\text{A} located at the upper decade at the 1000 seconds mark of the TCC curve and the its short circuit damage curve is located at the bottom three decades starting at the 0.01 seconds mark to the 10 seconds mark. From the TCC curve, the fuse’s TCC trip curves are both below and to the left of the line’s ampacity mark, its intermediate thermal overload limit curve and its short circuit damage curve hence the overhead line is well protected by the fuses. Fuse F632-645 has a continuous current rating of 250\text{A} which is within the NEC 240.101 maximum limit of the line conductor’s 300% ampacity of 1020\text{A}. Fuse F645 also has a continuous current rating of 200\text{A} which is within the NEC 240.101 maximum limit of the overhead line conductor’s 300% ampacity of 1020\text{A}.

4) LINE645-646 Protection Requirements, Ampacity Mark and Damage Curves

This is an overhead three phase distribution line connecting the branch segment between node 645 and node 646. The line phase conductors have ampacities of 230\text{Ampere}s and are each protected by two fuses. The upstream protective device is fuse F645-646 and the downstream protective device is Fuse F646. The TCC Curve for the overhead distribution line and its protective fuses is shown in Fig 11. The TCC curve shows the overhead line’s ampacity of 230\text{A} at the upper decade at the 1000 seconds mark of the TCC curve and the line’s short circuit damage curve located at the bottom three decades starting at the 0.01 seconds to the 10 seconds mark. From the TCC curve, the fuse’s TCC trip curves are both below and to the left of the line’s ampacity mark, its intermediate thermal overload limit curve and its short circuit damage curve hence the overhead distribution line is well protected by the fuses. Fuse F645-646 has a continuous current rating of 150\text{A} which is within the NEC 240.101 maximum limit of the line conductor’s 300% ampacity of 690\text{A}. Fuse F646 also has a continuous current rating of 125\text{A} which is within the NEC 240.101 maximum limit of the overhead line conductor’s 300% ampacity of 690\text{A}. 

3) LINE632-671 Protection Requirements, Ampacity Mark and Damage Curves

It is an overhead three phase distribution line connecting the branch segment between node 632 and node 671. The line phase conductors have ampacities of 730\text{Ampere}s and are each protected by two fuses. The upstream fuse is F632-671 and the downstream fuse is F671. The TCC Curve for the phase conductor and its protection fuses is shown in Fig 10. The TCC curve shows the overhead conductor ampacity of 730\text{A} located at the upper decade at the 1000 seconds mark of the TCC curve and the conductor short circuit damage curve located at the bottom three decades starting at the 0.01 seconds to the 10 seconds mark. From the TCC curve, the fuse’s trip curves are both below and to the left of the line’s ampacity mark, its intermediate thermal overload limit curve and its short circuit damage curve hence the overhead line is well protected by the fuses. Fuse F632-671 has a continuous current rating of 250\text{A} which is within the NEC 240.101 maximum limit of the line conductor’s 300% ampacity of 2190\text{A}. Fuse F671 also has a
Fig. 11: LINE645-646 Ampacity Mark, Short Circuit Damage Curve and Fuses F645-646 and F646 Trip Curves.

5) LINE650-632 Protection Requirements, Ampacity Mark and Damage Curves

This is an overhead three phase distribution line connecting the branch segment between node 650 and node 632. The line phase conductors have ampacities of 730 Amperes and are each protected by two fuses. The upstream protective device is fuse F650-632 and the downstream protective device is Fuse F632. The TCC Curve for the overhead distribution line and its protective fuses is shown in Fig 12. The TCC curve shows the overhead phase conductors ampacity of 730A at the upper decade at the 1000seconds mark of the TCC curve and the line’s short circuit damage curve located at the bottom three decades starting at the 0.01seconds mark to the 10seconds mark. From the TCC curve, the fuse’s TCC trip curves are both below and to the left of the line’s ampacity mark, its intermediate thermal overload limit curve and its short circuit damage curve hence the overhead line is well protected by the fuses. Fuse F650-632 has a continuous current rating of 350A which is within the NEC 240.101 maximum limit of the line conductor’s 300% ampacity of 2190A. Fuse F632 also has a continuous current rating of 125A which is within the NEC 240.101 maximum limit of the overhead line conductor’s 300% ampacity of 2190A.

Fig. 12: LINE650-632 Ampacity Mark, Short Circuit Damage Curve and Fuses F650-632 and F632 Trip Curves.

6) LINE671-680 Protection Requirements, Ampacity Mark and Damage Curves

This is an overhead three phase distribution line connecting the branch segment between node 671 and node 680. The line phase conductors have ampacities of 730 Amperes and are each protected by two fuses. The upstream protective device is fuse F671-680 and the downstream protective device is Fuse F680. The TCC Curve for the overhead distribution line phase conductor and its protective fuses is shown in Fig 13. The TCC curve shows the overhead line’s ampacity of 730A at the upper decade at 1000seconds mark of the TCC curve and the line’s short circuit damage curve located at the bottom three decades starting at the 0.01seconds mark to the 10seconds mark. From the TCC curve, the fuse’s TCC trip curves are both below and to the left of the line’s ampacity mark, its intermediate thermal overload limit curve and its short circuit damage curve hence the overhead line is well protected by the fuses. Fuse F671-680 has a continuous current rating of 150A which is within the NEC 240.101 maximum limit of the line conductor’s 300% ampacity of 2190A. Fuse F680 also has a continuous current rating of 125A which is within the NEC 240.101 maximum limit of the overhead line conductor’s 300% ampacity of 2190A.

Fig. 13: LINE671-680 Ampacity Mark, Short Circuit Damage Curve and Fuses F671-680 and F680 Trip Curves.

7) LINE671-684 Protection Requirements, Ampacity Mark and Damage Curves

This is an overhead three phase distribution line connecting the branch segment between node 671 and node 684. The line phase conductors have ampacities of 230 Amperes and are each protected by two fuses. The upstream protective device is fuse F671-684 and the downstream protective device is Fuse F684. The TCC Curve for the overhead distribution line phase conductor and its protective fuses is shown in Fig 14. The TCC curve shows the overhead line’s ampacity of 230A at the upper decade at the 1000seconds mark of the TCC curve and the line’s short circuit damage curve located at the bottom three decades starting at the 0.01seconds to the 10 seconds mark. From the TCC curve, the fuse’s TCC trip curves are both below and to the left of the line’s ampacity mark, its intermediate thermal overload limit curve and its short circuit damage curve.
curve hence the overhead line is well protected by the fuses. Fuse F671-684 has a continuous current rating of 150A which is within the NEC 240.101 maximum limit of the line conductor’s 300% ampacity of 690A. Fuse F684 also has a continuous current rating of 125A which is within the NEC 240.101 maximum limit of the overhead line conductor’s 300% ampacity of 690A.

8) **LINE684-611 Protection Requirements, Ampacity Mark and Damage Curves**

This is an overhead three phase distribution line connecting the branch segment between node 684 and node 611. The line phase conductors have ampacities of 230Amperes and are each protected by two fuses. The upstream protective device is fuse F684-611 and the downstream protective device is Fuse F611. The TCC Curve for the overhead distribution line phase conductor and its protective fuses is shown in Fig 15. The TCC curve shows the overhead line’s ampacity of 230A at the upper decade at the 1000seconds mark of the TCC curve and the line’s short circuit damage curve located at the bottom three decades starting from the 0.01seconds mark to the 10seconds mark. From the TCC curve, the fuse’s TCC trip curves are both below and to the left of the line’s ampacity curve mark, its intermediate thermal overload limit curve and its short circuit damage curve hence the overhead line is well protected by the fuses. Fuse F684-611 has a continuous current rating of 100A which is within the NEC 240.101 maximum limit of the cable’s 100% ampacity of 165A. Fuse F611 also has a continuous current rating of 75A which is within the NEC 240.101 maximum limit of the overhead line conductor’s 300% ampacity of 690A.

C. **Underground Cables Primary Protection Requirements, Ampacity Mark, Damage Curves and Protective Devices Curves**

The underground cables segments were given specific identification names whose codes were chosen based on the node points the cables is connected in between them. The fuses were given unique identification codes based on the node points of the underground cable they are set to protect. The upstream fuse was given a code in reference to the two nodes between which the underground cable has been connected and the downstream fuse also given a code based on the node the cable has been terminated at. The two underground cables were protected each by two fuses one connected at the source node and the other at the load and were referred as the upstream and the downstream fuse respectively. Table 2 gives the identification names and codes for all the four fuses used to protect the two underground cables.

<table>
<thead>
<tr>
<th>Cable Segment</th>
<th>Source Node</th>
<th>Load Node</th>
<th>Up-Stream Fuse</th>
<th>Down-Stream Fuse</th>
</tr>
</thead>
<tbody>
<tr>
<td>CABLE684-652</td>
<td>684</td>
<td>652</td>
<td>F684-652</td>
<td>F652</td>
</tr>
<tr>
<td>CABLE 692-675</td>
<td>692</td>
<td>675</td>
<td>F692-675</td>
<td>F675</td>
</tr>
</tbody>
</table>

1) **CABLE684-652 Protection Requirements, Ampacity Mark and Damage Curves**

This is a 15kV tape shielded All Aluminium (AA) underground cable connecting the branch segment between node 684 and node 652. The cable has an ampacity of 165Amperes and is protected by two fuses. The upstream protective device is Fuse F684-652 and the downstream protective device is Fuse F652. The TCC Curve for the cable and its protective fuses is shown in Fig 16. The TCC curve shows the cable ampacity of 165A at the upper decade at the 1000seconds mark of the TCC curve and the cable’s short circuit damage curve located at the bottom three decades between the 0.01 seconds mark and the 10 seconds mark. From the TCC curve, the fuse’s TCC trip curves are both below and to the left of the cable’s ampacity mark, its intermediate thermal overload limit curve and its short circuit damage curve hence the cable is well protected by the fuses. Fuse F684-652 has a continuous current rating of 100A which is within the NEC 240.101 maximum limit of the cable’s 100% ampacity of 165A. Fuse F652 also has a
continuous current rating of 75A which is within the NEC 240.101 maximum limit of the cable’s 100% ampacity of 165A.

D. Node Primary Protection Requirements, Ampacity Mark and Protective Devices Curves

All the 13 nodes were protected by a fuse. Table 3 gives the individual identification of all the 13 fuses used to protect the 13 nodes of the radial test feeder. Every node was given an identification code based on its reference numbers from the IEEE 13 node radial test feeder schematic diagram of Fig 6. The fuses also were given codes synonymous to the codes used in identifying the nodes.

<table>
<thead>
<tr>
<th>TABLE III: BUS/NODES PRIMARY PROTECTIVE FUSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>NODE ID</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>NODE611</td>
</tr>
<tr>
<td>NODE632</td>
</tr>
<tr>
<td>NODE633</td>
</tr>
<tr>
<td>NODE634</td>
</tr>
<tr>
<td>NODE645</td>
</tr>
<tr>
<td>NODE646</td>
</tr>
<tr>
<td>NODE650</td>
</tr>
<tr>
<td>NODE652</td>
</tr>
<tr>
<td>NODE671</td>
</tr>
<tr>
<td>NODE675</td>
</tr>
<tr>
<td>NODE680</td>
</tr>
<tr>
<td>NODE684</td>
</tr>
<tr>
<td>NODE692</td>
</tr>
</tbody>
</table>

1) NODE611 Protection Requirements, Ampacity Mark and Protective Devices Curves

This is a 4.16kV node with an ampacity of 230A and is protected by Fuse F611 having a continuous current rating of 75A. From the TCC protection coordination curve of Fig 18, the trip curve for Fuse F611 is located below and to the left of the node 611 ampacity mark at 1000 seconds point at the upper decade hence the node is protected by the fuse.

2) NODE632 Protection Requirements, Ampacity Mark and Protective Devices Curves

This is a 4.16kV node with an ampacity of 730A and is protected by Fuse F632 having a continuous current rating of 300A. From the TCC protection coordination curve of Fig 19, for the node, the trip curve for Fuse F632 is located below and to the left of the node’s ampacity mark at 1000 seconds mark at the upper decade hence the bus is well protected by the fuse.
3) NODE650 Protection Requirements, Ampacity Mark and Protective Devices Curves

This is a 4.16kV node with an ampacity of 750A and is protected by Fuse F650-632 having a continuous current rating of 350A. From the TCC protection coordination curve of Fig 21, the trip curve for Fuse F650-632 is located below and to the left of the node’s ampacity mark at 1000seconds mark at the upper decade hence the bus is well protected by the fuse.

4) NODE671 Protection Requirements, Ampacity Mark and Protective Devices Curves

This is a 4.16kV node with an ampacity of 730A and is protected by Fuse F671 having a continuous current rating of 200A. From the TCC protection coordination curve of Fig 22, the trip curve for fuse F671 is located below and to the left of the node’s ampacity mark at 1000seconds mark at the upper decade hence the bus is well protected by the fuse.

5) NODE675 Protection Requirements, Ampacity Mark and Protective Devices Curves

This is a 4.16kV node with an ampacity of 300A and is protected by Fuse F675 having a continuous current rating of 125A. From the TCC protection coordination curve of Fig 23, the trip curve for fuse F675 is located below and to the left of the node’s ampacity mark at 1000seconds mark at the upper decade hence the bus is well protected by the fuse.
6) NODE684 Protection Requirements, Ampacity Mark and Protective Devices Curves

This is a 4.16kV node with an ampacity of 230A and is protected by Fuse F684 having a continuous current rating of 125A. From the TCC protection coordination curve of Fig 24, the trip curve for fuse F684 is located below and to the left of the node’s ampacity curve at 1000 seconds mark at the upper decade hence the bus is well protected by the fuse.

1) In-Line Transformer Protection Requirements, Full Load Ampere Mark, Magnetizing Inrush Points and Damage Curves

The In-line transformer is a three-phase 500kVA step down transformer having a star grounded primary winding supplied at 4.16kV and a grounded wye secondary winding feeding power at a voltage of 0.48kV. The In-line transformer is connected on the primary side to node 633 and on the secondary side to node 634. The transformer is protected by two fuses F633 at the high voltage side and fuse F634 at the low voltage side. The TCC Curve for the transformer and its protective fuses is shown in the Fig 25. The TCC Curve shows that the transformer full-load ampere (FLA) of 601.407A is located at the upper decade at the 1000 seconds mark and its magnetizing inrush current of 4811.253A with a multiplier 8 of the FLA located at the bottom decade at 0.1 second marks of the TCC Curve. The transformer mechanical damage curve is shown located at the 3rd and 4th decade of the TCC Curve starting at the 2 seconds mark to the 4 seconds mark for the In-Line transformer in Fig 25. The thermal damage curve is shown located at the 3rd and 4th decade of the TCC coordination curve starting from the 2 seconds mark to the 50 seconds mark.

Fuse F633 has a continuous current rating of 150A which is within the NEC 450.3 maximum limit of 300% of the transformer full load amperes (FLA) of 208.2A. NEC 450.3 stipulates that an upstream fuse used in protecting the transformer primary windings must have a rating not exceeding 300% of the primary side full load current. Fuse F633 trip curve is located above and to the right of the transformer full load current (FLA) of 69.4A and its magnetizing inrush current point of \(8 \times FLA\) at 4811.253A. This clearly shows that the trip curve for fuse F633 protects the In-Line transformer’s FLA mark and its magnetizing inrush current point.

Fuse F634 has a continuous current rating of 630A and is within the NEC 450.3 maximum limit which stipulates that a downstream fuse protecting the secondary windings of a transformer should have a current limit not exceeding 125% of the transformer full load currents. Fuse F634 continuous current rating of 630A is within NEC 450.3 maximum limit of 125% of the FLA of 751.8A. Fuse F634 trip curve is located below and to the left of both the transformer thermal damage curve and the transformer mechanical damage curves hence fuse F634 protects the In-Line transformer.

---

**TABLE IV: Transformer Protective Devices**

<table>
<thead>
<tr>
<th>Location ID</th>
<th>Initial</th>
<th>Secondary</th>
<th>Up-Stream Fuse</th>
<th>Down-Stream Fuse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substation Transformer T1</td>
<td>GRID NODE 650</td>
<td>NODE 650</td>
<td>FGRID</td>
<td>F650</td>
</tr>
<tr>
<td>In-Line Transformer T2</td>
<td>NODE 633</td>
<td>NODE 634</td>
<td>F633</td>
<td>F634</td>
</tr>
</tbody>
</table>

---

**Fig. 23: NODE675 Ampacity Mark and Fuse F675 TCC Protection Curve**

**Fig. 24: NODE684 Ampacity Mark and Fuse F684 TCC Protection Curve**

---

**E. Transformer Primary Protection Requirements, Full Load Ampere Mark, Magnetizing Inrush Points and Damage Curves**

IEEE 13 node radial test feeder has two transformers one at the power grid supply side referred to as the substation transformer T1 connected between the grid node and node 650, and the other connected between nodes 633 and 634 referred to as the In-Line transformer T2. The two transformers are each protected by two fuses one on the primary side and the other on the secondary side as seen from Table 4. Only the in-line transformer T2 has been analyzed for protection coordination since it forms part of the IEEE 13 node radial test feeder at a voltage profile of 4.16kV.

DOI: [http://dx.doi.org/10.24018/ejers.2019.4.9.1549](http://dx.doi.org/10.24018/ejers.2019.4.9.1549)
IV. CONCLUSION

By application of the feeder protection rules NEC 240.101, the transformer protection rules NEC 450.3, the IEEE Standard 241 and the ANSI/IEEE regulations for distribution feeder protection, the IEEE 13 node radial test feeder was correctly modeled in electrical transient analysis program (ETAP) for fuse-fuse protection. Fuses were used for both primary and back up protection for the four major components of the feeder. The fuses and their settings were adequately chosen so that they coordinate.

REFERENCES


Mr Kemei Peter Kirui is a Kenyan born at Kiptere Location, Kericho County on 14th May 1983. He trained as an Electrical Engineer and graduated with a Bachelor’s degree in Electrical and Communication Engineering from Moi University, Eldoret Kenya on 10th December 2009. He also trained in Technology Education and graduated with a PGDE in Technology Education from Moi University on 16th December 2014. He trained as an Energy Auditor with Kenya Association of Manufacturers (KAM) on 2016. He has also trained as a Power Systems Engineering Examiner with the Kenya National Examination Council (KNEC) on 2014.
He has worked for KNEC since 2014 to date as an Electrical Power Systems Engineering Examiner. He worked as a lecturer teaching Electrical Engineering at Zetech University Nairobi Kenya on the year 2015 before proceeding to Moi University Eldoret, Kenya as an Assistant Lecturer in the department of Electrical and Electronic Technology where he works up to date.
Mr Kemei is a registered graduate engineer by the Kenya Engineers Registration Board (ERB). His areas of interest in research are: Power Systems Protection; Power Systems Distribution Networks Planning; Renewable Energy, especially Wind Energy.