Modeling and Detection of Turn-to-Turn Faults in Shunt Reactors

KRZYSZTOF SOLAK¹, FRANK MIESKE², AND SEBASTIAN SCHNEIDER²
¹Department of Electrical Power Engineering, Wrocław University of Science and Technology, 50-370 Wrocław, Poland
²Siemens AG Berlin, 80333 Munich, Germany

Corresponding author: Krzysztof Solak (krzysztof.solak@pwr.edu.pl)

ABSTRACT In this paper, the analysis and simulation of shunt reactor turn-to-turn faults, as well as the algorithms for their detection, are presented. A simple equivalent circuit of a shunt reactor applicable for a small number of short-circuited turns was developed and applied to simulate such faults. It is shown why the commonly applied differential relays are not able to detect turn-to-turn faults. Then three new algorithms are introduced, and their performance is analyzed for simulated internal faults. The proposed methods are based on zero-sequence reactance, negative-sequence reactance, and phase impedance. The sensitivity and security of the presented methods are discussed. The proposed algorithms’ performance has been tested with the signals generated with the use of the MATLAB/Simulink program. The results confirm that the proposed algorithm can effectively improve the detection of turn-to-turn faults. The paper ends with recommendations for the setting of the proposed protection schemes.

INDEX TERMS Negative-sequence criteria, shunt reactor, shunt reactor protection, transient analysis, turn-to-turn faults.

I. INTRODUCTION The shunt reactors are generally parallel connected at both sides of the long overhead transmission lines or pipe-type cables [1], [2]. They are used to consume the capacitive reactive power produced by line/cable capacitance, which helps to control/stabilize the system voltage. It is claimed that they can be classified as Flexible AC Transmission Systems (FACTS) technology [3]. Shunt reactors can be built as a dry-type or oil-immersed type. They can be connected directly to the line, bus, or the tertiary winding of a power transformer.

Turn-to-turn faults in shunt reactors are not common failures, but they are very dangerous, and thus they should be detected very quickly. Unfortunately, the standard longitudinal differential protection [4]–[6] is not able to see turn-to-turn faults in the shunt reactor. The differential current after fault inception is zero, independently of the number of shorted turns. The same situation is observed for negative-sequence differential protection (ANSI 87Q) [7], [8]. Therefore, the shunt reactors need additional criteria for detecting turn-to-turn faults. Some solutions of the problem can be found in [9]–[14], they include:

− impedance relays, that may be used as primary or backup protection [10],
− split phase protection schemes used only for shunt reactors with two parallel windings [10], [11],
− earth-fault overcurrent protection controlled by the directional zero-sequence element [9], [10],
− earth fault overcurrent protection supported by a directional negative-sequence relay [10],
− Buchholz relays, used only for the oil-immersed type of shunt reactor [9], [10],
− hybrid differential algorithms, where the difference between normalized negative-sequence terminal voltage and normalized-negative sequence reactor current phasors are taken into account [12],
− an approach based on the relationship between flux and current of shunt reactor [13],
− differential protection, where the magnitude of the second central moment (SCM) is calculated from the residual and differential current [14].

In this paper, three methods for detecting turn-to-turn faults based on zero-sequence reactance, negative-sequence reactance, and phase impedance are proposed. They are very simple to implement and can be used for any type of shunt reactor, for the units connected directly to the line or to the transformer tertiary winding.

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It should be noted that the information about the useful model of a shunt reactor for turn-to-turn fault simulation is hardly available in the literature. Therefore, a suitable model for modelling turn-to-turn faults in a shunt reactor has been developed and is discussed in the paper.

The structure of the paper is as follows. In section 2, Thevenin’s equivalent circuit with a fictitious winding representing the short-circuited turns is described and analyzed. Next (Section 3), the proposed protection methods are introduced. The testing results of the presented methods for various disturbances are discussed in Section 4. Section 5 summarizes this paper with conclusions.

II. DEVELOPMENT OF SHUNT REACTOR MODEL FOR TURN-TO-TURN FAULTS ANALYSIS

Generally, the shunt reactor can be connected to a power system in two manners. The three-phase shunt reactor may be solidly grounded and directly connected to the line, or it may remain ungrounded and connected to a transformer tertiary winding (Fig. 1a, b).

Both configurations were taken into account when analyzing turn-to-turn faults since the connection way affects the current fault level, symmetrical components flow, etc. The easiest way to calculate the currents during a turn-to-turn short-circuit is to use an equivalent Thevenin’s circuit (similar as it was proposed for a power transformer in [15]).

Here, another simplification is also adopted; namely, the fictitious winding replaces affected turns. This idea was discussed in [15], and here it is recalled for the convenience of the reader. The circuit representing the short-circuit itself (Fig. 2a) is replaced by the fictitious winding circuit (Fig. 2b). As a result, the current $I_1$ is smaller than the current $I$:

$$I_1 = I \left(\frac{w_1 - w_z}{w_1}\right)^2$$

while the equivalent circuit impedance is equal:

$$Z_1 = Z \left(\frac{w_1}{w_1 - w_z}\right)^2$$

where: $w_1$ and $w_z$ are numbers of turns of the winding and those being short-circuited, respectively.

Equations (1) and (2) show the scale of difference, which is acceptable for a small number of faulted turns. It is certainly so for one or just a few short-circuited turns. As a result, using such an approach with a fictitious winding makes it possible to develop an equivalent circuit, representing the shunt reactor for any location of turn-to-turn fault with a small number of turns involved [15].

The proposed equivalent Thevenin’s circuit for turn-to-turn faults in shunt reactors is presented in Fig. 3. Fig. 3a shows the scheme for a shunt reactor directly connected to the line, while the equivalent circuit for a shunt reactor connected to the transformer tertiary winding is illustrated in Fig. 3b.

It can be noted that when the number of short-circuited turns is high, the resistance $R_{ZZ}$ is much smaller than the reactance $X_{ZZ}$ and may be neglected. However, cases of a very small number of short-circuited turns are of considerable interest. In such cases, the resistance is comparable, or sometimes even much larger than the reactance [16]–[18].

The shunt reactor copper losses (in one phase) become:

$$P_{cu} = \frac{I^2 R_K}{3}$$

$\text{(3)}$
The value of resistance in the equivalent circuit can be calculated according to:

\[
R_{ZZ} = R_K \left( \frac{w_Z}{w_K} \right) \tag{7}
\]

If the resistance of the short-circuited turns is related to the number of turns \(w_K\), their resistance \(R_Z\) in the equivalent circuit amounts to:

\[
R_Z = R_K \left( \frac{w_K}{w_Z} \right) \tag{8}
\]

where: \(w_Z\) - number of faulted turns, \(w_K\) - number of turns of the winding.

The reactance \(X_{ZZ}\) eventuates from the leakage cross flux. It depends to a large degree on the location of the short-circuited turns in the cross-section of the winding, on the number of the affected turns, and on the cross-section of them. It can only be estimated on the ground of experiments on the model of the shunt reactor; in most cases, the exact value cannot be easily calculated as in the case of resistance \(R_{ZZ}\). In [16]–[18], it is shown that the reactance \(X_{ZZ}\) is comparable to the resistance \(R_{ZZ}\) for a small number of shorted turns. Therefore, for further analysis, it was assumed that \(X_{ZZ} = R_{ZZ}\).

The equivalent Thevenin’s circuit depicted in Fig. 3 can be analyzed analytically in an easy way. Thanks to this, it is possible to determine the short-circuit current level and other related quantities during turn-to-turn faults. It is a significant advantage since then adequate protection settings can also be determined.

For the equivalent Thevenin’s circuit shown in Fig. 3a, assuming that \(X_{ZZ} = R_{ZZ}\), one gets:

\[
Z_{ZZ} = \left| \frac{Z_{ZZ}}{jX_{ZZ}} \right| = \left| R_{ZZ} + jX_{ZZ} \right| = \sqrt{2}R_{ZZ} \tag{9}
\]

Then using (7), one obtains:

\[
Z_{ZZ} = \sqrt{2}R_K \left( \frac{w_Z}{w_K} \right) \tag{10}
\]

and the impedance recalculated on the \(w_K\) side is equal to:

\[
Z_Z = \sqrt{2}R_K \left( \frac{w_K}{w_Z} \right) \tag{11}
\]

If it is further assumed that \(Z_T \ll Z_Z\) and \(Z_G \ll Z_Z\), then:

\[
E_{ZZ} = U_f \left( \frac{w_Z}{w_K} \right) \tag{12}
\]

The fault current amplitude under turn-to-turn fault with a small number of short-circuited turns can be calculated analytically according to:

\[
I_{ZZ} = E_{ZZ} \left( \frac{w_Z}{Z_{ZZ}} \right) = \frac{U_f}{\sqrt{2}R_K} \tag{13}
\]

and the fault current recalculated on the \(w_K\) side (seen at the terminal of the shunt reactor) equals:

\[
I_Z = \frac{U_f}{\sqrt{2}R_K} \left( \frac{w_Z}{w_K} \right) \tag{14}
\]
It can be noted that the current in the faulted turns \( (12) \) is independent of the number of turns involved. It depends mainly on the value of copper power losses in the shunt reactor.

The equations \( (3) - (14) \) can be used to calculate fault current during a turn-to-turn fault in a shunt reactor analytically. Moreover, if it is assumed that the value of shunt reactor copper power losses is very small and it can be expressed by the formula \([11]\):

\[
P_{cu} \approx 0.0015Q_K \approx 0.0015 \frac{U^2}{X_K} \approx 0.0015 \frac{3U_f^2}{X_K}
\]

then equation \( (6) \) can be rewritten as:

\[
R_K \approx 0.0015X_K
\]

and after simple transformations, formula \( (13) \) takes the following form:

\[
I_{Z2} = \frac{Q_K}{3 \sqrt{2} \cdot 0.0015 \cdot U_f}
\]

and the current at the shunt reactor terminals caused by a short-circuit can be calculated according to:

\[
I_Z = \frac{Q_K}{3 \sqrt{2} \cdot 0.0015 \cdot U_f} \left( \frac{w_Z}{w_K} \right)
\]

Equation \( (18) \) shows that the analyzed short-circuit causes a relatively low current at the shunt reactor terminals. However, at the same time, an extremely large current \( (17) \) flows in the coil winding. For a sample shunt reactor with the following parameters \([19]\) \( Q_K = 25 \text{MVA}, U_f = 230 \text{kV/}\sqrt{3}, w_K = 1530, I_n = 62.75 \text{A} \), the terminal current \( I_Z \) for single-turn fault \( w_Z = 1 \) is about 19.33A (0.3pu), while the current in the faulted turns is as high as 29.5kA (470pu).

It can be concluded that it is possible to determine the fault current in two ways:

1. analytically, with the use of the equations \( (3) \) to \( (18) \);
2. by simulation, with the use of an appropriate digital model based on the circuits from Fig. 3.

Note that for further testing of proposed fault detection methods, more valuable is the way #2. Therefore, the digital models of the shunt reactor corresponding to the equivalent Thevenin’s circuits from Figs. 3a and b were developed in MATLAB/Simulink environment \([20]\). They comprise the model of the shunt reactor with the fictitious winding itself as well as the equivalent impedance of the feeding system dependent upon the assumed source short-circuit power. The developed model also includes appropriate CTs (100A/1A, 5P30, 20VA) installed at the shunt reactor terminals.

### III. PROPOSED METHODS FOR DETECTION OF TURN-TO-TURN FAULTS

Generally, the standard stabilized differential protection \((ANSI 87)\) is still recommended for the protection of shunt reactors. As shown in the above example, the current terminal \( I_Z \) for a single-turn fault is about 0.3pu, which means that it is not that small. However, due to the construction of shunt reactors, the differential currents are negligible; thus, the turn-to-turn faults are not seen by the standard differential protection. Therefore, new methods for the detection of turn-to-turn faults in shunt reactors are still needed.

All the schemes described below have directional features; however, they are based on impedance components, which is different from how the standard directional elements \((ANSI 67)\) are organized \([9], [10]\).

![Diagram](image-url)

**FIGURE 4. Zero-sequence reactance directional method: a) proposed scheme and logic, b) directional characteristic.**

The first proposed method (Option 1) is based on zero-sequence reactance measured at the unit terminals. The logic scheme of the algorithm is presented in Fig. 4a. The proposed scheme is very simple since it needs only two settings. The estimated zero-sequence reactance allows to determine whether the fault is within the zone or out-of-zone with respect to the shunt reactor terminals (see Fig. 4b); it works like a directional element. The discrimination threshold for the reactance is set slightly above zero to avoid numerical problems. Here, the zero-sequence current is also checked, and the final protection reaction is enabled only when the \( 3I_0 \) level exceeds a pre-defined threshold (dependent on the network asymmetry and possible measurement errors \([9], [12]\)). Additional time delay is introduced to stabilize the solution during transients. This algorithm can be used only for the shunt reactors directly connected to the line (Fig. 3a) since otherwise (Fig. 3b), the zero-sequence quantities are not observed.
The second method is very similar to the first one; however, the negative-sequence reactance and the negative-sequence current are used (Fig. 5, Option 2). This algorithm is universal, for it can be used for shunt reactors connected to the power system both directly and by transformer tertiary winding.

The last proposed approach (Option 3) is based on the phase impedances seen from the shunt reactor terminals. Here, the terminal voltages and currents are used, and the phase impedances are calculated according to the formula:

$$Z_x = \frac{U_x}{I_x}$$  \hspace{1cm} (19)

where: $x$ – phase L1 . . . L3.

The logic scheme and the proposed protection characteristic are illustrated in Fig. 6. It can be noted that this option can be simplified when only the reactance is taken into account. It should be mentioned that this method can be applied for both shunt reactor connection manners.

In order to identify the faulty phase during the turn-to-turn fault, the following phase selection procedure can be used. For methods 1 and 2, the amplitude of phase currents can be analyzed, and the highest value of the amplitude indicates the faulty phase. For method 3, it is checked which measured phase impedances enter the tripping area, and based on this information, phase selection is realized.

### IV. TESTING OF THE PROTECTION SCHEMES WITH SIMULATION SIGNALS

The proposed protection algorithms have been tested for strong ($S''_k = 8$GVA) and weak ($S'_k = 0.1$GVA) equivalent power systems for single-phase-to-ground and two-phase external faults as well as internal turn-to-turn faults. Selected examples are shown below.

#### TABLE 1. Preliminary testing of methods no. 1 and no. 2 (shunt reactor directly connected to the line) for the strong ($S''_k = 8$GVA) equivalent power system.

| Number of shorted turns | $X_x$ (pu) | $3I_x$ (pu) | $X_z$ (pu) | $3I_z$ (pu) |
|------------------------|-----------|------------|-----------|------------|
| 1                      | -0.0031   | 0.3064     | -0.0031   | 0.3064     |
| 2                      | -0.0031   | 0.6125     | -0.0031   | 0.6125     |
| 4                      | -0.0031   | 1.223      | -0.0031   | 1.223      |
| 5                      | -0.0031   | 1.528      | -0.0031   | 1.528      |
| 8                      | -0.0031   | 2.44       | -0.0031   | 2.44       |
| 15                     | -0.0031   | 4.552      | -0.0031   | 4.552      |
| 31                     | -0.0031   | 9.303      | -0.0031   | 9.303      |
| 77                     | -0.0031   | 22.38      | -0.0031   | 22.38      |
| 153                    | -0.0031   | 42.4       | -0.0031   | 42.4       |
Tables 1-8 show preliminary testing results for methods no. 1 and no. 2 for internal turn-to-turn faults. Note that for the modeled shunt reactor [19] the maximum number of turns shorted \( w_Z = 153 \) represents 10\% of the winding with a total number of turns \( w_K = 1530 \). It can be seen that significantly lower values of the negative- and zero-sequence reactances are obtained for strong power system equivalent. What’s more, the value of calculated reactance for the whole range of the assumed number of shorted turns is constant for the strong power system (Table 1 and Table 2), while for the weak equivalent source, it is slightly varying (Table 5 and Table 6).

As mentioned in Chapter II, the value of reactance \( X_{ZZ} \) was assumed to be at the level of resistance \( R_{ZZ} \) (\( X_{ZZ} = R_{ZZ} \)) since it can hardly be determined. Nevertheless, in order to check how this value influences the results, additional tests were conducted for various values of \( X_{ZZ} \) (Table 3, Table 4, Table 7, Table 8). It can be concluded that for various...
$X_{Z2}/R_{Z2}$ ratios, the estimated zero- and negative-sequence reactances are almost constant despite the apparent change of the zero/negative-sequence currents. It confirms that the lack of precise knowledge of $X_{Z2}$ doesn’t significantly affect the performance of both proposed methods.

Presented results prove that the assumed settings for methods no. 1 and no. 2 are selected correctly. The negative-sequence current and the zero-sequence current are greater than 0.1pu for all considered cases. Besides, the values of negative-sequence reactance and zero-sequence reactance are lower than 0.01pu. Therefore, both methods can detect all turn-to-turn faults firmly, even with a single turn shorted.

In Figs. 7-9, the testing results of method no. 3 are presented. As one can see, the results obtained are identical for both shunt reactor connection ways and both values of short circuit power (power system strength). It can also be noted that for various $X_{Z2}/R_{Z2}$ ratios (Fig. 9), the real part of the calculated phase impedance is changing significantly, while the imaginary part is almost constant. Nevertheless, the estimated phase impedances for all turn-to-turn faults are located inside the proposed characteristic (Fig. 9b); thus, all the cases are correctly recognized by the proposed algorithm.
The testing results for selected simulated internal and external fault cases are presented in Figs. 10-13. All of the cases represent fault conditions for the strong equivalent power system ($S''_k = 8GVA$). Note that turn-to-turn fault cases were generated in equivalent Thevenin’s circuit (Fig.3). Consequently, steady-state and faulty conditions are simulated separately for such fault. Figs.10 and 11 show a combination of both of these states.

In Fig. 10 and Fig. 11, the cases of single-turn ($w_1 = 1$) internal faults are shown for shunt reactor connected directly to the line (Fig. 10) and when it is connected to the transformer tertiary winding (Fig. 11). It is visible that
all proposed methods correctly detected this internal fault. For both shunt reactor connections, the measured zero- and negative-sequence reactances are negative, whereas the zero/negative-sequence current is high enough to exceed the setting (Fig. 10c, d and Fig. 11c). The phase impedances enter the tripping zone, which means that analyzed internal faults are correctly recognized (Fig. 10e and Fig. 11d).

If these results are compared with those in [9], one can conclude that the proposed methods assure faster detection of the faults. In [9], the voltage-polarized ground directional overcurrent element was tested for detection of turn-to-turn fault at 40 percent of the A-phase winding counting from a neutral point. The registered fault detection time was 15 cycles [9], while the fault detection time
offered by all here proposed methods was a little more than one cycle.

In addition, the effect of asymmetry of the phase impedances of the shunt reactor was considered. Generally, phase impedances in a real shunt reactor are not identical – a slight asymmetry can be observed. The maximum tolerance of phase impedances is ±2% [1], and here such differences were also assumed. It means that impedance in phase L1 was 1pu, in phase L2 = 1.02pu, and in phase L3 = 0.98pu. Fig. 12 presents the case of single-turn ($w_z = 1$) internal fault for such a shunt reactor connected directly to the line. It can be concluded that all proposed
methods identify this fault without any problem. It can be observed that zero- and negative-sequence currents are higher than zero before fault (due to shunt reactor asymmetry), but this did not worsen the short-circuit detection and did not pick-up the proposed methods before the short-circuit occurred.

Fig. 13 presents the internal single-turn fault for the shunt reactor connected directly to the line during the energization of the unloaded line. It was assumed that the line circuit breaker was closed in a controlled manner at three consecutive phase voltage peaks [11]. It means that the effect of saturation of shunt reactor can be omitted in
such a situation – the inrush currents were reduced to the minimum. Therefore, the influence of energization of the unloaded line is only observed. Note that the line circuit breaker can also be synchronized for closing when the three phase voltages cross zero [10]. Then the inrush current is maximum, and the proposed fault detection algorithms would be blocked by appropriate stabilization, e.g. the second harmonic ratio [1], [10]. In the assumed case (when inrush current is minimum), the three proposed methods quickly and reliably detect the turn-to-turn internal fault in phase L1.
despite the transient conditions caused by the unloaded line energization. Besides, the operation of the proposed methods was also verified for a situation where only the unloaded line energized (without internal fault) – in such a case, the three methods remain stable without issuing the tripping decision.

The following presented cases are external two-phase faults for the shunt reactor connected directly to the line.
(Fig. 14) and connected to the transformer tertiary winding (Fig. 15). In the first case (Fig. 14), all proposed methods were appropriately performed, i.e., no tripping command was generated. The measured zero- and negative-sequence reactances were positive (Fig. 14c, d), and the phase impedance trajectories (Fig. 14e) were outside the tripping zone (after the transient delay \( \Delta t = 20 \) ms expired). When the shunt reactor was connected to transformer tertiary winding, both methods also operated correctly – here, no tripping decision was issued. The measured negative-sequence reactance was close to 1pu (positive value, see Fig. 15c), which indicates an external disturbance. Method no. 3 worked adequately since the phase impedance trajectories were also outside the tripping zone in the steady-state after the fault (Fig. 15d). Besides, the terminal currents in faulty phases were lower than the threshold (Fig. 15e), which also blocked the tripping command.

V. CONCLUSION

In this paper, modeling turn-to-turn faults in shunt reactors and the new algorithms for detecting such short-circuits are described. The paper presents a simplified approach to calculating the turn-to-turn fault currents in cases of a very small number of short-circuited turns, in which the winding resistance becomes dominant. The equations for the analytical calculation of fault current and its level during turn-to-turn fault are derived and discussed.

Despite in the analytical analysis, it was first assumed that \( X_{ZZ} = R_{ZZ} \), all the proposed fault detection methods were tested for various reactance values in the range \( X_{ZZ} = 0.01 \div 3R_{ZZ} \), which may have an impact on the current fault level during turn-to-turn faults. However, it was confirmed that the lack of precise knowledge of \( X_{ZZ} \) doesn’t significantly affect the performance of the proposed methods.

The testing results revealed that it is possible to detect turn-to-turn faults in shunt reactors with use of proposed methods. Among the considered solutions, the most universal are methods no. 2 and 3; they can be used for shunt reactors connected directly to the line and shunt reactors connected to the tertiary transformer windings. Method no. 2 seems to be the best since it is very simple, very sensitive, and behaves secure for considered external faults without the need for additional criteria.

It can be noted that the proposed methods need appropriate stabilization under magnetizing inrush – such information is included in Table 9. For example, the second harmonic ratio can be applied for stabilization of the proposed algorithms [1], [10]. In addition, synchronized switching (point-on-wave switching) may be applied in many practical configurations. Then the inrush current can be reduced to a minimum [10], [11] – which significantly improves the operation of protective relays.

In Table 9, the final recommendations for each method are shown.

| Method no. 1 | Settings | Comments |
|--------------|----------|----------|
| Method no. 2 | \( X_0 = 0.01X_0 \), \( I_0 = 0.1I_0 \) | applicable only for shunt reactors connected directly to the line stabilization needed under shunt reactor energization cases |
| Method no. 3 | proposed characteristic (Figure 5b) \( \frac{I_1}{I_2} = 1.2, 1.3 = 0.8I_0 \) | stabilization needed under shunt reactor energization cases |

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KRZYSZTOF SOLAK was born in Środa Śląska, Poland, in 1982. He received the M.Sc. and Ph.D. degrees from the Wrocław University of Science and Technology (WUST), Wrocław, Poland, in 2006 and 2010, respectively. At present, he is an Assistant Professor with the Department of Electrical Power Engineering, WUST. He has published more than 40 articles in journals and conference proceedings and four patents. His research interests include artificial intelligence (neural networks, fuzzy systems, and genetic algorithms) for power system protection and digital simulation of transient phenomena.

FRANK MIESKE was born in Berlin, Germany, in 1967. He received the Dipl.-Ing. degree from Technical University Berlin, Berlin, Germany, in 1996. He has been with the Department of Energy Automation, Siemens AG, Berlin, since 2001. He is a Product Architect for siprotec transformer protection devices and worked in the development of protection devices mainly in the areas of signal processing, transformer differential protection, and voltage regulation. Due to his many years as an expert and numerous inventions, he has extensive know-how in these areas and is involved in many innovations.

SEBASTIAN SCHNEIDER was born in Frankfurt (Oder), Germany, in 1981. He received the degree in electrical power engineering from the Brandenburg University of Technology, Cottbus, Germany, and the Dipl.-Ing. degree in electrical engineering, in 2009. Since 2012, he has been with Siemens AG, Nuremberg. He is the responsible Product Lifecycle Manager for transformer and generator differential protection, voltage regulator, high speed busbar transfer, and parallel switching devices.