Reliability of Substation Configurations

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Introduction

While one of the strongest points in a power system is the electric substation, it still contains what could be described as weak points or points of failure that would lead to loss of load. By knowing how to calculate the reliability of different substation configurations, an engineer can use this information to help design a system with the best overall reliability. But determining the reliability of a substation can also be important for existing installations as it can help locate weak points that may be contributing to overall system unreliability. This paper will present an overview in determining substation reliability indices and then through the use of an example show how various configurations can be compared.

Before embarking on determining reliability, the purpose of the assessment should be clearly evident as this may affect the choice of which method is used to determine reliability. A method may look at how substation reliability affects the overall system reliability, how the system reliability affects substation reliability [1], or substation reliability decoupled from the rest of the power system. Methods may also be better suited to specific types of substations such as transmission and switching, distribution or industrial. Switching and reconfiguration events typically will use a more complex method of reliability assessment than those used to look at a single substation design, This paper will concentrate on determining the reliability of a substation not including system wide effects.

Substation Evaluation Basics adapted from [2]

Billington describes what he considers the five essential steps to be carried out when performing substation evaluation. While much work on this topic has been carried out since this early publication, these steps remain valid and provide a starting point for this discussion on reliability evaluation. The steps are listed below followed by a short description of each. The method used to carry out each of the five steps can vary depending on the chosen reliability assessment.

- Physical System Description
- Performance Criteria
- Reliability Indices
- Failure Mode and Effects Evaluation
- Accumulation of Failure Effects and Summary

Physical System Description

An important step when beginning the reliability assessment is to determine the boundaries of the system that will be studied. A system study would include not only the substation, but also the incoming and outgoing feeders as well as determining the impact the substation has on the system and ultimately customer satisfaction. While many of the early reliability studies focused on transmission and switching substations in isolation from the electrical system, there now are a number of methods that include the impact of the substation on the system [1,3,4]. More recent works have extended both the system and decoupled analysis to the distribution system, which has its own unique load point reliability indices [8,9].

After the boundary has been determined, the next step is to determine in what detail will components be represented. In the simplest case, a two state, up/down model can be used to represent all components, or if more detail is required higher order models can be utilized. The detail needed will be dependant on what type of failure modes being considered. Figure 1 shows Markov component models of increasing complexity [9].

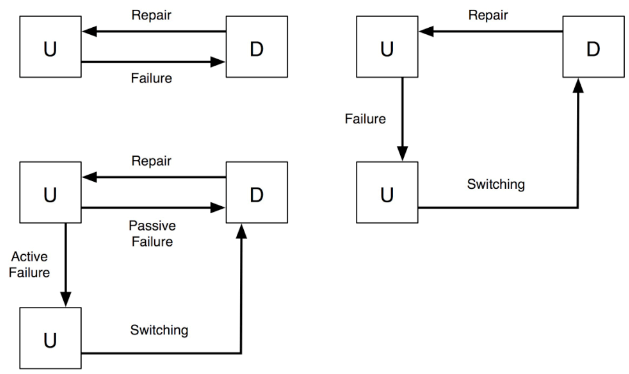

Figure 1: Component Models

Finally, the component reliability data must be specified.

Performance Criteria

If any system constraints are needed for the study, they would be added in this step. This would include items such as transmission line carrying constraints, bus voltages and overloads. The criteria specified in this step will vary greatly upon what type of reliability study is being carried out. A system study may include a large number of operating constraints while an industrial substation study may include only a few.

Reliability Indices

During this step, a level of satisfactory performance must be developed. Billington lists a number of possibilities ranging from a positive/negative status describing whether or not a system reaches the operational goal, to a numerical number that describes the "availability of the system," a per-unit time the system meets the reliability goal.

Some commonly used substation reliability indices are listed below.

- Failure rate λ (/yr)
- Duration (min/yr)
- Repair time r (hrs)
- Availability (%)

Other indices may be of importance when dealing with a more system wide view or when concerned with cost of the loss of load.

- SAIFI, SAIDI, CAIDI, ASAI (distribution system indices)

- LOLP, LOLE, MELL (load point indices)

Failure Modes and Effects Evaluation

For each failure mode, the effects of the failure and what action must be taken to correct the failure need to be determined. The effect of each failure can then be listed according to the likelihood of the event. The following steps can provide a framework for gathering the needed information from each failure mode.

1. Protection system status and resulting breaker action.
2. Have breaker actions caused load interruption
3. Have any performance criteria violations occurred
    a. If yes, then determine actions to mitigate violations
        i. Transfer possible?
        ii. Repair required?
4. Record all effects by terminal affected, along with the probability of the event and its duration.

Later papers have described failure modes in a somewhat different manner categorizing them into 4 basic groups [3,4,5] or combinations thereof [6].

- Passive failure events
- Active failure events
- Stuck-condition of breakers
- Overlapping failure events

Passive failure events are component failures that do not activate the protection system such as unknown open circuit conditions or unintentional operation of a circuit breaker.

As expected, if a passive failure does not activate the protection system, an active failure is an event that causes the protection system to operate and isolate a failed component. A simple example of an active failure event would be a fault on a bus and the subsequent operation of breakers to "seal off" the area from the rest of the station.

If during the above fault one of the primary breakers failed to operate and a backup or secondary breaker had to operate to isolate the faulted area, this would be termed a 'stuck-condition of breakers' failure mode. The station may still remain in operation, but a larger portion has become inoperable than in the active failure mode.

An overlapping failure is when a failure has occurred and before the failure has been fixed, another failure occurs. When carrying out a reliability study, it is common to only look at events that involve two components. According to Allan [5] the probability of higher order failures is negligible.

A number of methods have been used in determining the final substation indices. The majority of these methods represent each component as a Markov model, which allows various analytical methods to be used to solve for the substation reliability. Another possible method, which will be illustrated by an example presented later in this paper, is the minimal cut-set method based on the criterion of continuity of service.

A downside to using Markov models is that all transition rates must be constant, implying that the time spent in a state is exponentially distributed. While this may be true of failure times, the repair times may be considerably different. Billington and Lian have developed a Monte Carlo approach to solving a system with nonMarkovian models. More information on this approach can be found in [10].

Accumulation of Failure Effects and Summary

The final step is to list all system failures by the probability of occurrence. This will provide a clear picture of scenarios that will cause the most problems. To find the system reliability (or in this case, substation reliability), combine the system failure probabilities and frequencies. Each failure state is an exclusive state, so the probability of occurrence of system failure is the sum of all the failure event probabilities. The product of occurrence of failure event and the duration can be used to determine the probability of the failure state.

Substation Configurations Primer

Before embarking on determining substation reliability indices, it is helpful to be familiar with some of the common substation layouts and their corresponding names. Certain configurations may be more suited to a specific task, so the equipment in each type of substation may vary, but with the exception of switching stations, they generally will include a transformer, circuit breakers and isolation switches. This section will give a brief introduction to 6 of the more common substation bus configurations followed by a number of advantages/disadvantages [7]. It will conclude with a cost comparison of each configuration. Plan and elevation views of each type of configuration can be found in the appendix.

Typical Bus Configurations

Single Bus

Figure 2 shows the one-line diagram of a single bus substation configuration. This is the simplest of the configurations, but is also the least reliable. It can be constructed in either of low profile or high-profile arrangement depending on the amount of space available. In the arrangement shown, the circuit must be de-energized to perform breaker maintenance, which can be overcome by the addition of breaker bypass switches, but this may then disable protection systems.

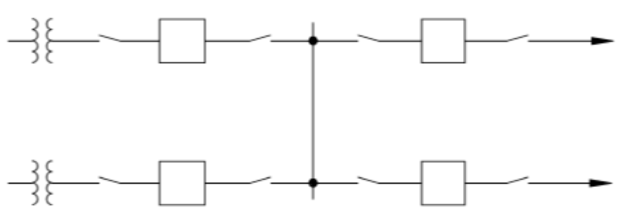

Figure 2: Single Bus

Single Bus Advantages:

- Lowest cost
- Small land area
- Easily expandable
- Simple in concept and operation
- Relatively simple for the application of protective relaying

Single Bus Disadvantages:

- Single bus arrangement has the lowest reliability
- Failure of a circuit breaker or a bus fault causes loss of entire substation
- Maintenance switching can complicate and disable some of the protection schemes and overall relay coordination

Sectionalized Bus

Figure 3 shows the layout of a sectionalized bus, which is merely an extension of the single bus layout. The single bus arrangements are now connected together with a center circuit breaker that may be normally open or closed. Now, in the event of a breaker failure or bus bar fault, the entire station is not shut down. Breaker bypass operation can also be included in the sectionalized bus configuration.

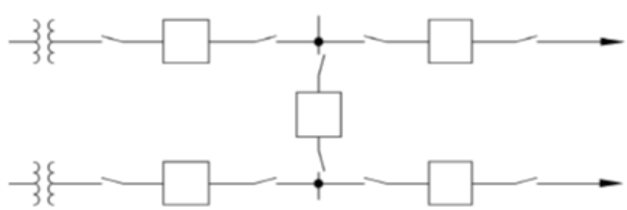

Figure 3: Sectionalized Bus

Sectionalized Bus Advantages:

- Flexible operation
- Isolation of bus sections for maintenance
- Loss of only part of the substation for a breaker failure or bus fault

Sectionalized Bus Disadvantages:

- Additional circuit breakers needed for sectionalizing, thus higher cost
- Sectionalizing may cause interruption of non-faulted circuits

Main and Transfer Bus

A main and transfer bus configuration is shown in Figure 4. There are two separate and independent buses; a main and a transfer. Normally, all circuits, incoming and outgoing, are connection the main bus. If maintenance or repair is required on a circuit breaker, the associated circuit can be then fed and protected from the transfer bus, while the original breaker is isolated from the system.

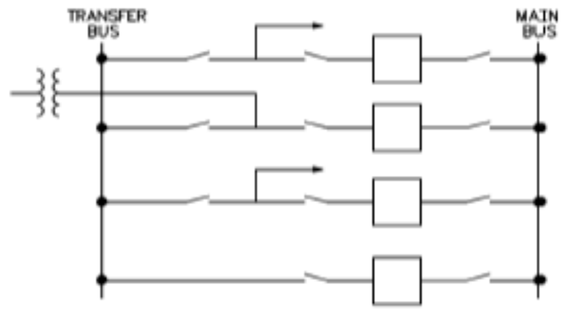

Figure 4: Main and Transfer Bus

Main and Transfer Bus Advantages:

- Maintain service and protection during circuit breaker maintenance
- Reasonable in cost
- Fairly small land area
- Easily expandable

Main and Transfer Bus Disadvantages:

- Additional circuit breaker needed for bus tie
- Protection and relaying may become complicated
- Bus fault causes loss of the entire substation

Ring Bus

Figure 5 depicts the layout of a ring bus configuration, which is an extension of the sectionalized bus. In the ring bus a sectionalizing breaker has been added between the two open bus ends. Now there is a closed loop on the bus with each section separated by a circuit breaker. This provides greater reliability and allows for flexible operation. The ring bus can easily adapted to a breaker-and-a-half scheme, which will be looked at next.

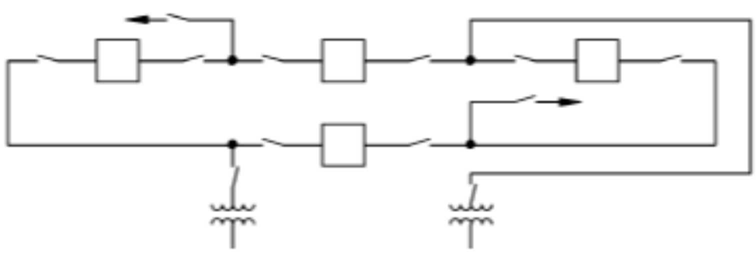

Figure 5: Ring Bus

Ring Bus Advantages:

- Flexible operation
- High reliability
- Double feed to each circuit
- No main buses
- Expandable to breaker-and-a-half configuration
- Isolation of bus sections and circuit breakers for maintenance without circuit disruption

Ring Bus Disadvantages:

- During fault, splitting of the ring may leave undesirable circuit combinations
- Each circuit has to have its own potential source for relaying
- Usually limited to 4 circuit positions, although larger sizes up to 10 are in service. 6 is usually the maximum terminals for a ring bus

Breaker-and-a-Half

A breaker-and-a-half configuration has two buses but unlike the main and transfer scheme, both busses are energized during normal operation. This configuration is shown in Figure 6. For every 2 circuits there are 3 circuit breakers with each circuit sharing a common center breaker. Any breaker can be removed for maintenance without affecting the service on the corresponding exiting feeder, and a fault on either bus can be isolated without interrupting service to the outgoing lines. If a center breaker should fail, this will cause the loss of 2 circuits, while the loss of an outside breaker would disrupt only one. The breaker-and-a-half scheme is a popular choice when upgrading a ring bus to provide more terminals.

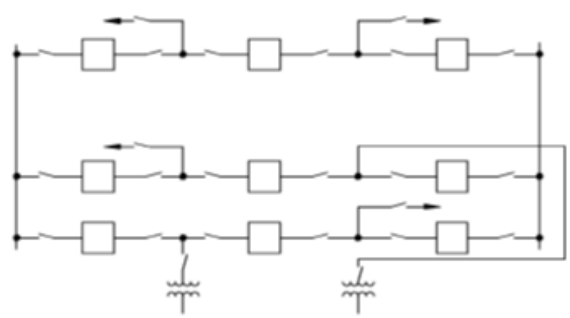

Figure 6: Breaker-and-a-Half

Breaker-and-a-Half Advantages:

- Flexible operation and high reliability
- Isolation of either bus without service disruption
- Isolation of any breaker for maintenance without service disruption
- Double feed to each circuit
- Bus fault does not interrupt service to any circuits
- All switching is done with circuit breakers

Breaker-and-a-Half Disadvantages:

- One-and-a-half breakers needed for each circuit
- More complicated relaying as the center breaker has to act on faults for either of the 2 circuits it is associated with
- Each circuit should have its own potential source for relaying

Double Breaker-Double Bus

The final configuration shown is the double breaker – double bus scheme in figure 7. Like the breaker-and-a-half, the double breaker-double bus configuration has two main buses that are both normally energized. Here though, each circuit requires two breakers, not one-and-a-half. With the addition of the extra breaker per circuit, any of the breakers can fail and only affect one circuit. This added reliability comes at the cost of additional breakers, and thus is usually only used at large generating stations.

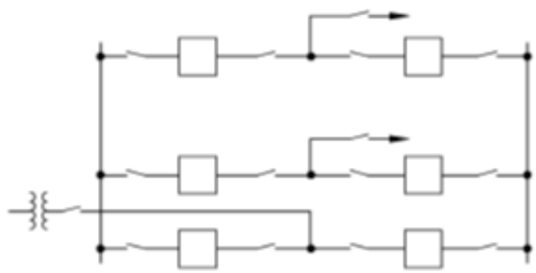

Figure 7: Double Breaker-Double Bus

Double Breaker-Double Bus Advantages:

- Flexible operation and very high reliability
- Isolation of either bus, or any breaker without disrupting service
- Double feed to each circuit
- No interruption of service to any circuit from a bus fault
- Loss of one circuit per breaker failure
- All switching with circuit breakers

Double Breaker-Double Bus Disadvantages:

- Very high cost – 2 breakers per circuit

Comparison of Bus Configuration Costs

Table 1 gives a relative cost comparison of the different substation configurations discussed above [7]. The comparisons are done with four circuits for each configuration, but do not include costs associated with a power transformer. Note that the cost relationships between the configurations may change, depending on the number of circuits used and protective relaying devices that are used.

Table 1: Cost Comparison of Substation Configurations

Configuration	Relative Cost Comparison
Single Bus	100%
Sectionalized Bus	122%
Main and Transfer Bus	143%
Ring Bus	114%
Breaker-and-a-Half	158%
Double Breaker-Double Bus	214%

Substation Reliability Comparison Example adapted from [11]

The following example will compare the reliability of five different substation configurations as shown in Figure 8. The indices developed for each will be the average failure rate, average outage duration, and annual outage time. The components modeled in the example will be transformers, bus bars and breakers. Although the original example included a system study with distribution indices, only substation indices will developed in this discussion.

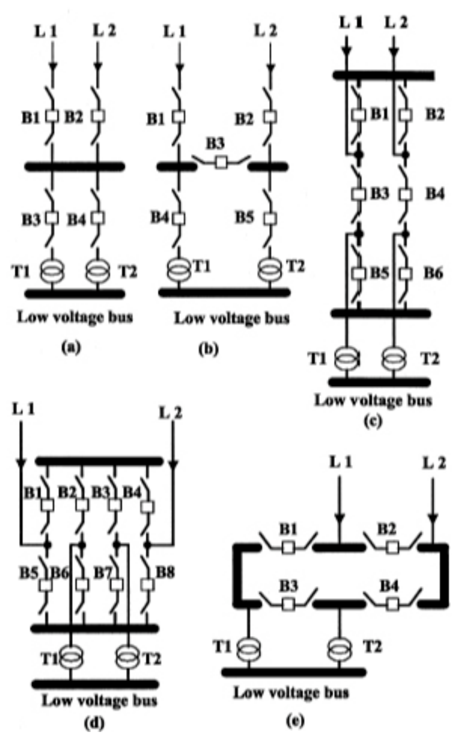

Figure 8: Studied Substation Configurations

a. Single bus
b. Sectionalized single bus
c. Breaker-and-a-half
d. Double breaker-double bus
e. Ring bus

Two lines, either of which can supply the total need of the station, feed each configuration. The stations reliability will be computed ignoring line failure and also with line failures included.

The reliability of each configuration will be evaluated using the minimal cut-set method based on the criterion of continuity of service.

A minimal cut-set is a set of components that when all fail, the continuity of service is lost, but if any one of the components doesn't fail, the continuity remains.

The cut-sets will be categorized according to their failure mode and then further divided into active and passive failures. The failure modes considered in this example are listed below.

- First order total failure (both active and passive failures)
- First order active failure
- First order active failure with stuck condition of circuit breaker
- Second order overlapping failure event involving two components

When the minimal cut-sets have been formed, the reliability indices for each cut-set mode can be calculated. Each minimal cut-set can be represented as a parallel configuration of components and the various cut-sets together can be represented as a series configuration [12, 13].

To show how the cut-set method would work, the failure rate for the single bus configuration will be calculated. For this calculation, the incoming lines T1 and T2 will be assumed to have 100% reliability. To better recognize the cut-sets, the single bus configuration has been redrawn below in Figure 9.

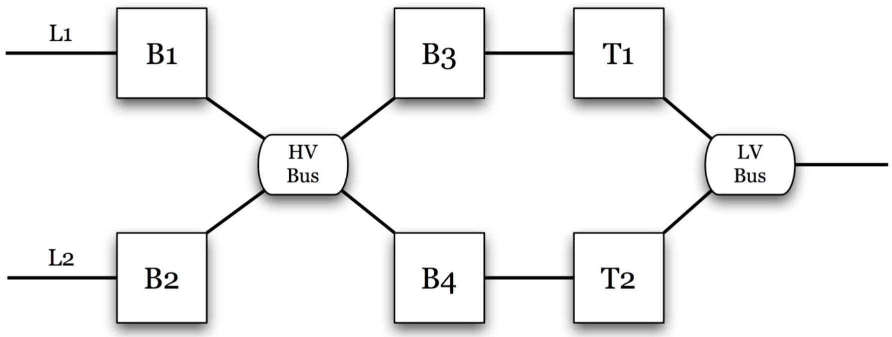

Figure 9: Single Bus Diagram

The component reliability data is shown in Table 2. λT is the total failure rate of a component and λA is the active failure rate of a component.

Table 2: Substation Component Reliability Data

Component	**λT** (/yr)	**λA** (/yr)	**λM** (/yr)	**MTTR** (hours)	**MTTM** (hours)
Line	0.046	0.046	0.5	8	8
Transformer	0.015	0.015	1.0	15	120
Breaker	0.006	0.004	1.0	4	96
Bus bar	0.001	0.001	0.5	2	8

The first order total station failure modes are the failures of the high voltage bus and low voltage bus. The failure of either bus interrupts the station continuity.

$$\lambda_t = 0.001 + 0.001 = 0.002 \tag{1}$$

The first order active failure modes are B1, B2, B3 and B4. To illustrate this, consider a fault occurs on L1 and breaker B1 fails to open, breaker B2 will operate, thus breaking station continuity. Similar scenarios can show that B2-B4 are also active failure modes.

$$\lambda_a = 0.004 + 0.004 + 0.004 + 0.004 = 0.016 \tag{2}$$

The first order active failure plus stuck breakers (p=1) are T1+B3 stuck and T2+B4 stuck.

$$\lambda_s = 0.015 + 0.015 = 0.030 \tag{3}$$

The total failures overlapping total failures are B1+B2, B3+B4, B3+T2, B4+T1 and T1+T2. The parallel failure rate of each paralleled group of two components can be calculated as follows.

$$\lambda_p = \frac{\lambda_1 e^{-\lambda_1} + \lambda_2 e^{-\lambda_2} - (\lambda_1+\lambda_2)e^{-(\lambda_1+\lambda_2)}}{e^{-\lambda_1} + e^{-\lambda_2} - e^{-(\lambda_1+\lambda_2)}}$$

$$\begin{aligned} \lambda_{B1+B2} &= 7.1357 \cdot 10^{-5} \\ \lambda_{B3+B4} &= 7.1357 \cdot 10^{-5} \\ \lambda_{B3+T2} &= 1.772 \cdot 10^{-4} \\ \lambda_{B4+T1} &= 1.772 \cdot 10^{-4} \\ \lambda_{T1+T2} &= 4.401 \cdot 10^{-4} \end{aligned} \quad (4)$$

The total failure rate is then the sum of the paralleled rates.

$$\lambda_o = 2 \cdot \left(7.1357 \cdot 10^{-5}\right) + 2 \cdot \left(1.772 \cdot 10^{-4}\right) + 4.401 \cdot 10^{-4} = 9.372 \cdot 10^{-4} \quad (5)$$

The overall substation failure rate is then the sum of failure rates for each failure mode.

$$\lambda = \lambda_t + \lambda_a + \lambda_s + \lambda_o = 0.0489 \quad (6)$$

Annual outage time for the substation configuration can be found in a similar manner along with the average outage duration.

$$\begin{aligned} U &= U_t + U_a + U_s + U_o = 3.53 \\ r &= \frac{U}{\lambda} = 72.15 \end{aligned} \quad (7\text{-}8)$$

Complete reliability indices for the five substation configurations with 100% reliable source lines are listed in Table 3.

Table 3: Substation Reliability Indices (Ignoring Line Failure)

Configuration	λ (/yr)	r (min)	U (min/yr)
a	0.0489	72.15	3.53
b	0.0453	71.95	3.26
c	0.00301	184.56	0.56
d	0.00567	124.216	0.70
e	0.0174	81.88	1.42

For comparison, the indices with the impact of source line failures is shown in Table 4. Notice that trends seen in Table 3 are also seen in Table 4. Failure rates increase between 0.9% and 35% and U increases from between 2.8% and 53%. This show what effect source line failures can have on the substation indices, but it does not change the relationships between the configurations. Configuration ‘c’ is still the most reliable scheme and ‘a’ remains the worst.

Table 4: Substation Reliability Indices (Including Line Failures)

Configuration	λ (/yr)	r (min)	U (min/yr)
a	0.0549	80.50	4.42
b	0.0459	76.35	3.50
c	0.00356	175.76	0.63
d	0.00572	125.14	0.72
e	0.0235	92.20	2.17

These results could then be fed into a composite system, which would then ultimately lead to load point indices.

References

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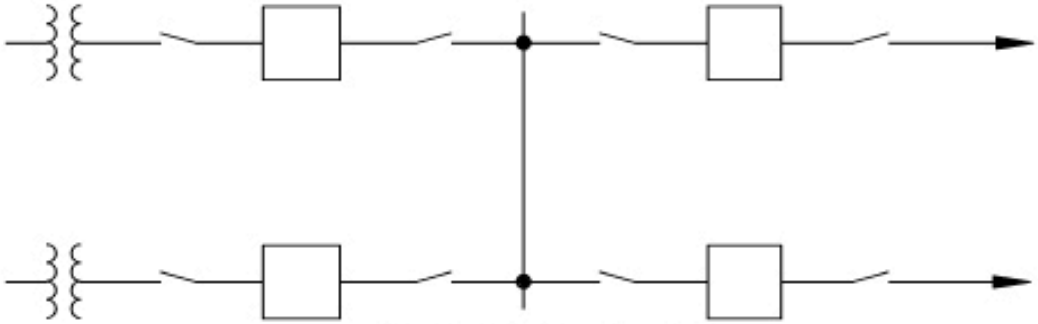
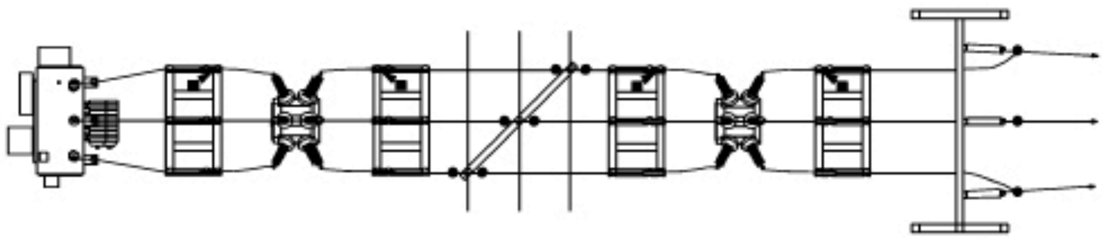
Appendix

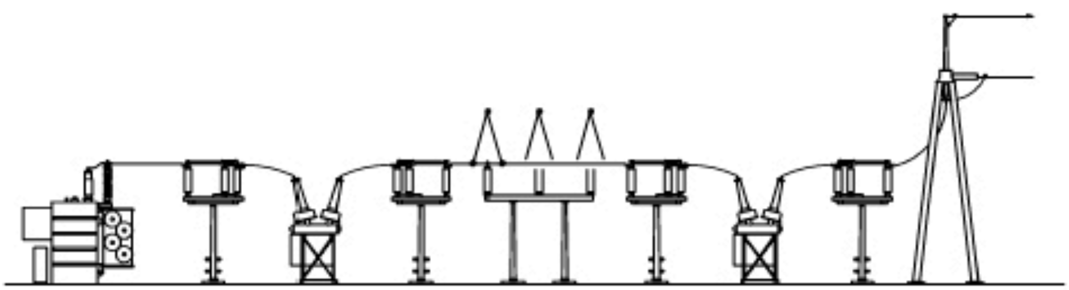
Single Bus - Low Profile



TYPICAL ONE-LINE DIAGRAM

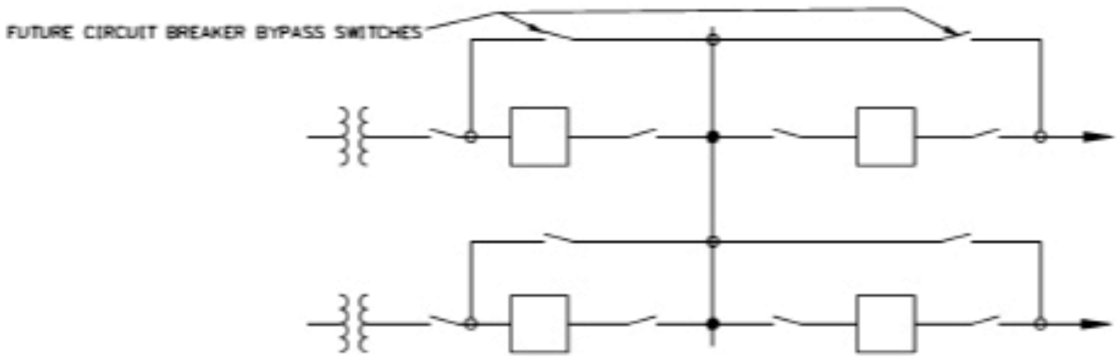


PLAN VIEW—TYPICAL BAY

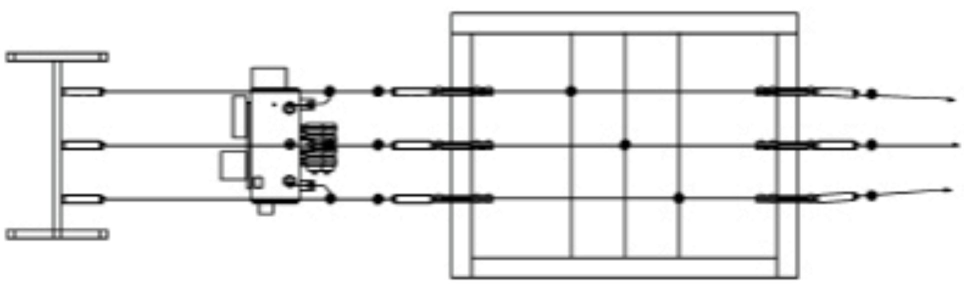


ELEVATION—TYPICAL BAY

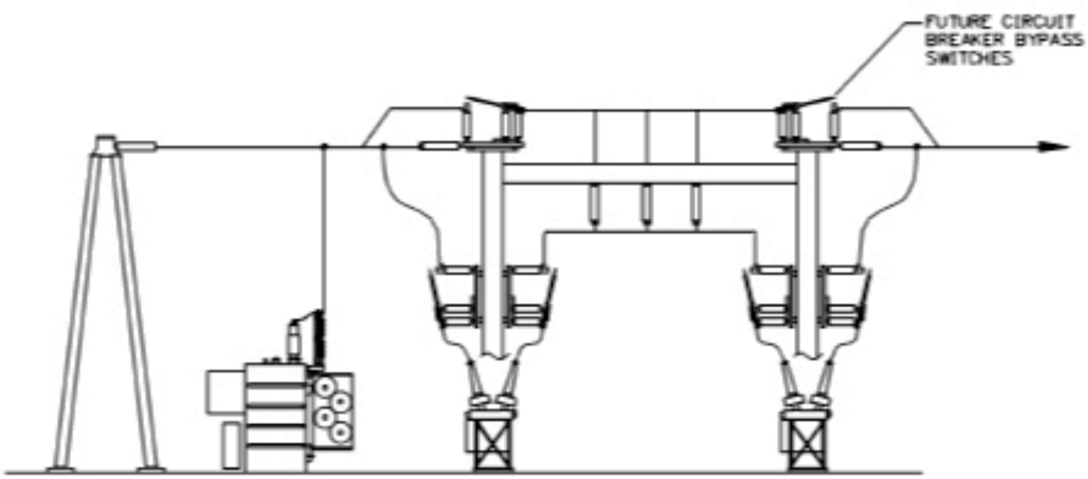
Single Bus - High Profile



TYPICAL ONE-LINE DIAGRAM

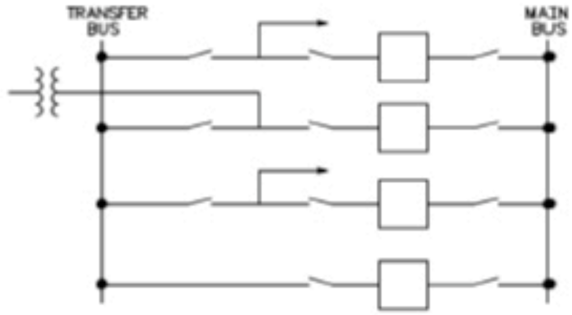


PLAN VIEW–TYPICAL BAY

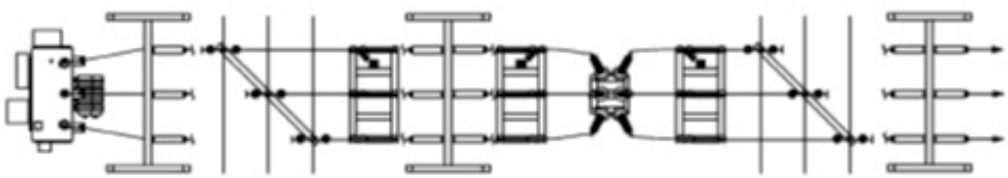


ELEVATON–TYPICAL BAY

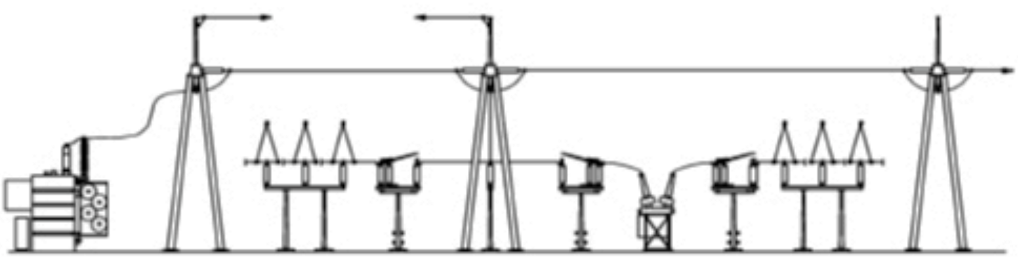
Main and Transfer Bus - Low Profile



TYPICAL ONE-LINE DIAGRAM

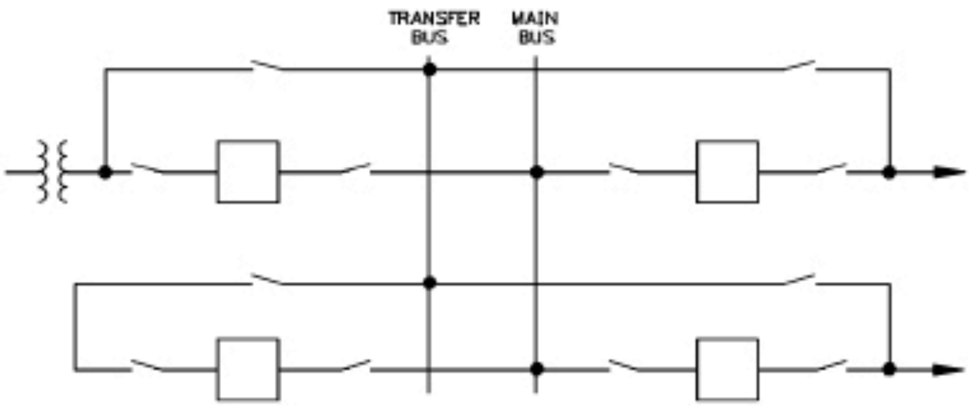


PLAN VIEW-TYPICAL BAY

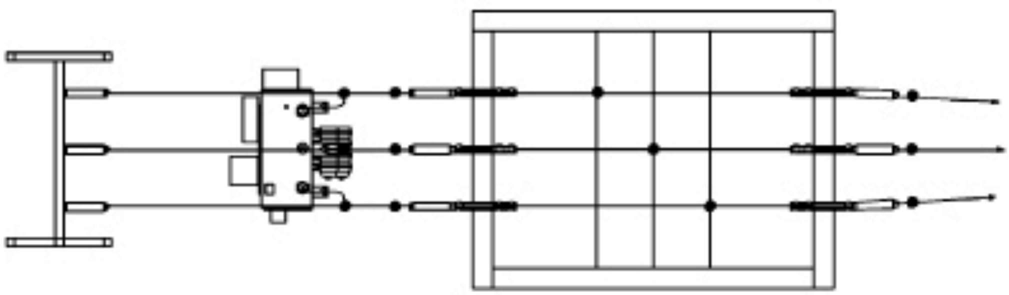


ELEVATION TYPICAL BAY

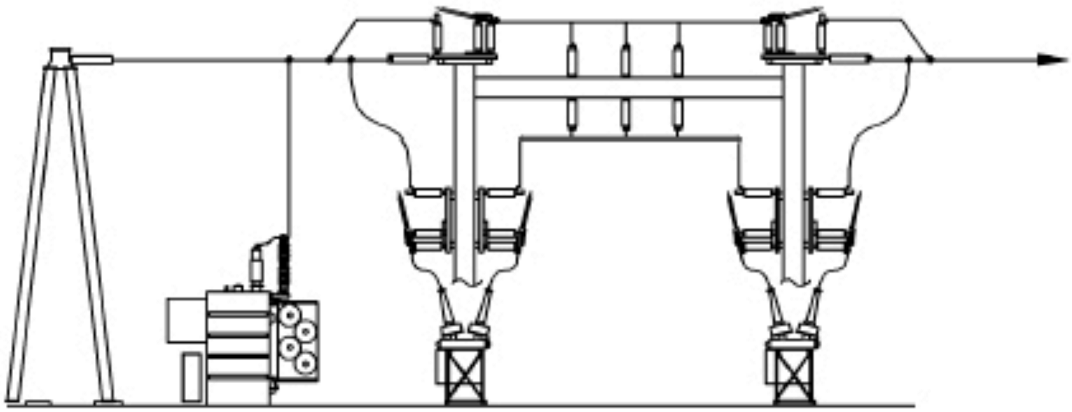
Main and Transfer Bus - High Profile



TYPICAL ONE-LINE DIAGRAM

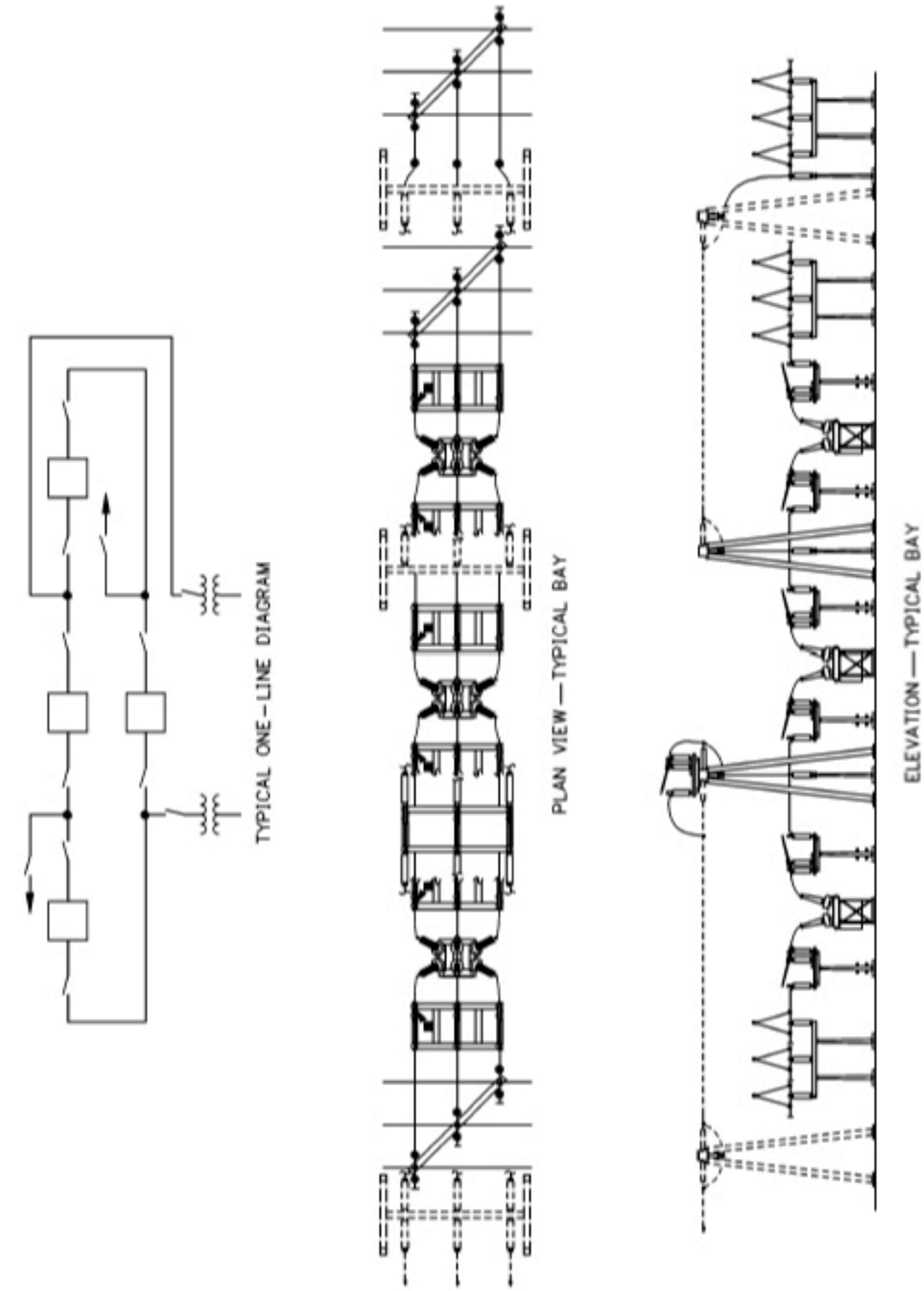


PLAN VIEW—TYPICAL BAY

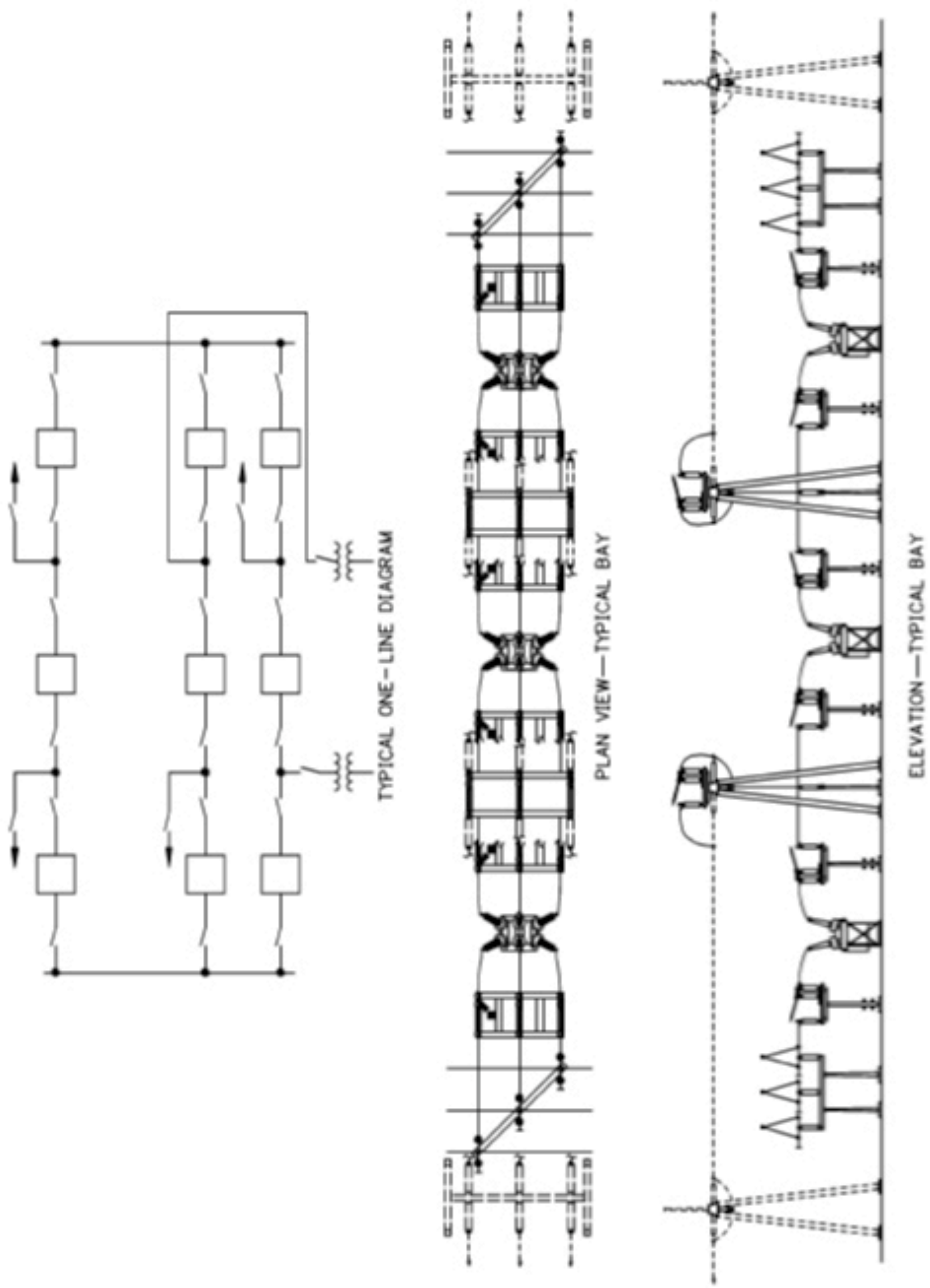


ELEVATON—TYPICAL BAY

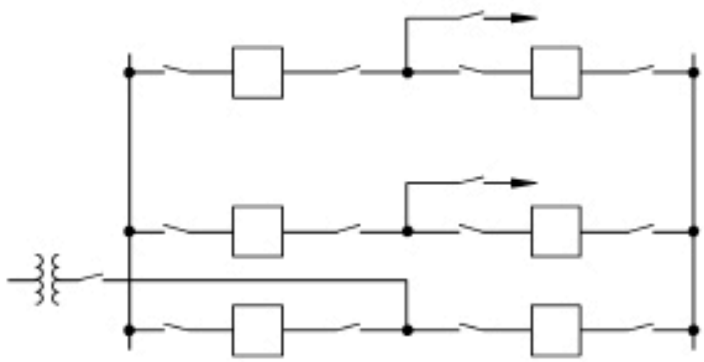
Ring Bus


TYPICAL ONE-LINE DIAGRAM
PLAN VIEW — TYPICAL BAY
ELEVATION — TYPICAL BAY

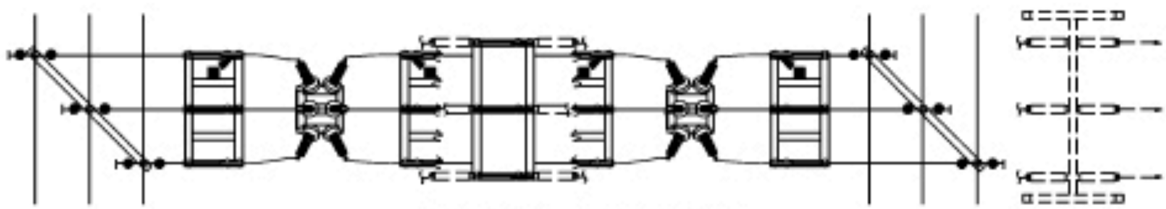
Breaker-and-a-Half



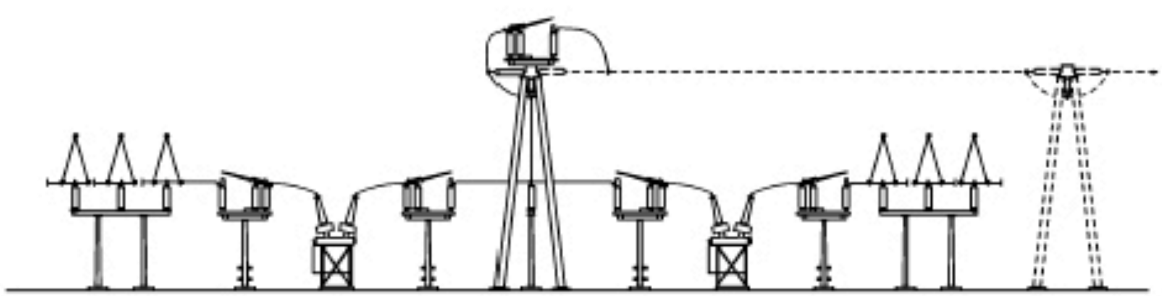
Double Breaker-Double Bus



TYPICAL ONE-LINE DIAGRAM



PLAN VIEW—TYPICAL BAY



ELEVATION—TYPICAL BAY