Alteration from radial to ring power distribution to improve system reliability: A case study

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Abstract. Outage of power system supplying oil and gas production facilities causes hundreds of barrel of oil equivalent loss per hour. Hence, there is a need to improve the supply continuity by e.g. altering the power distribution configuration from radial to ring. However, switching to ring configuration demands adjustment related to system capability in delivering higher current, taking longer route, or handling higher fault current. This study develops an approach to assess those requirements and benefits. The evaluation includes load flow, short circuit, protection relay coordination, and reliability analysis. This study aims to evaluate the existing system capability in applying ring configuration and recommend any required adjustment. This study also intends to estimate the reduction of outage duration. Overall, the existing radial power distribution system can be switched to ring configuration with several adjustments. The ring application offers 43.07 percent annual outage reduction from 17.322 to 9.861 hours annually.

1. Introduction
In production sensitive industries, as in the power system of interest here, a short outage means significant loss of revenue. Hence, improving supply continuity becomes a substantial effort and can be achieved through various strategies. These include switching the topology from radial to ring configuration [1]. This paper evaluates engineering feasibility aspects with practical approach adopted and developed from best practice and related codes and standards. There are a couple of aspects that needs to be evaluated before applying ring configuration: (i) outage reduction benefit and (ii) devices capability in delivering higher current, taking longer route, or handling higher fault current from both forward and reverse direction.

The purpose of this study is to assess the ring configuration application and to recommend any adjustment to make it feasibly applied. This study also aims to estimate the number of outage reduction as the benefit of ring application. The study evaluates that ring configuration can be applied with the condition of increased cable size in two sections, utilization of directional type of feeder protection relay, and re-set generator protection relay. The expected outage duration from ring application is 9.861 hours annually, a reduction from the existing radial configuration of 17.322 hours annually.

2. Method
This study intends to evaluate an alteration plan from radial to ring power distribution through several steps of analyses as shown in Figure 1.
2.1. Build the network model
The simplified network model was used (Figure 2) to ease readers to understand the big picture without losing the substance [2]. However, more complex model was actually used in software to conduct analyses in the following steps. When actual data were not available, input data was based on software library and typical data. Typical values, where used, were taken from IEC 60909-2 where possible. Other sources of data such as specific cable impedance were obtained from vendor. The network consisted of four observed buses: PS-201, PS5-BG1, PS4-AC3, and PS3-AC2. It run in radial configuration as the circuit breakers that connected PS3-AC2 and PS4-AC3 are opened (see Figure 2) and used only for backup purpose. Alteration to ring configuration was achieved by closing those circuit breakers.

2.2. Load flow analysis
The load flow analysis result was used to evaluate cable loading and voltage profile of each bus [3]. In order to evaluate voltage profile, the following classification was used:
- Normal (−2.5% < voltage < 2.5%)
- Marginal under voltage (−5% < voltage <= −2.5%)
- Marginal overvoltage (2.5% <= voltage < 5%)
- Critical (5% <= voltage <= −5%)

While cable loading used the following classification:
- Marginal (80% <= load < 90%)
- Critical (load >= 90%)

The classification did not act as allowable operating voltage boundary yet it provided reference to set priority in making development plan. For instance, critical devices should be the first priority in corrective action plan. Besides the normal radial and ring configuration, load flow analysis run for contingency cases in ring application to evaluate if the cable still able to perform under worst-case situation. The extra cases were:
- Using ring configuration but the line that connects PS-201 to PS3-AC2 was disconnected.
- Using ring configuration but the line that connect PS-201 to PS5-BG1 was disconnected.
2.3. Short circuit analysis
The analysis was delivered in two conditions: momentary duty which runs 3-phase short circuit at the first 1/2 cycle to confirm busbar rating, and interrupting duty that runs 3-phase short circuit at 1.5 – 4 cycle to confirm circuit breaker rating [4]. Prefault voltage was set to 105% of nominal voltage. The ratio between short circuit current and devices capability was classified into following categories:
- Critical: short circuit current reaches 100% of device capability.
- Marginal: short circuit current reaches 90% of device capability.

2.4. Protection relay coordination analysis
The analysis was carried out only to ring configuration, while the existing radial protection was assumed to be correct. This analysis intended to determine the requirement to correctly protect the system when fault happened so that the fault point is quickly isolated from the system and only a minimum section should be isolated. The analysis was carried out with several limitations as follows:
- Time interval between characteristic curves should be equal or more than 0.4 seconds [5].
- Iset should be between 1.2 maximum load current and 50% of minimum short circuit current.
- Short circuit current used in protection relay evaluation is the 30th cycle of short circuit current at each fault location.
- Characteristic curves used ETAP library for the corresponding manufacturer and model of the relays.

2.5. Reliability analysis
The analysis aimed to determine the outage rate of each distribution route as in Table 1. Figure 3 shows the simplified model used for the calculation. Reliability on the upstream and downstream side of the model are not considered. The outage rate used for the calculation shown in Table 2 is based on the best practice in the company. Equations (1) and (2) are the formula to calculate the outage duration of supplying B1 load through radial and ring configuration, respectively. For ring configuration, it is assumed that the disconnection of one of the section A, B, C, or D caused by maintenance does not cut off the supply to the load. The same approach as equations (1) and (2) applies to all other routes.

\[
DB_{1, \text{radial}} = D_f + D_d + D_f + D_m + D_m + D_m + D_m
\]

\[
DB_{1, \text{ring}} = D_f + D_d + (D_f + D_d + D_m + D_m + D_f) + D_m
\]

Table 1. Distribution route.

| Load | Route |
|------|-------|
| B1   | S–0–1 | 0–2–3–1 |
| B2   | S–0–2 | 0–1–3–2 |
| B3   | S–0–2–3 | 0–1–3 |

Figure 3. Supply reliability model.
### Table 2. Outage rate.

| Equipment  | Unpredicted Downtime / Failure | Predicted Downtime / Maintenance |
|------------|--------------------------------|---------------------------------|
|            | Frequency (occurrence per year) | Mean Time to Repair (per occurrence, in year) | Frequency (occurrence per year) | Preventive Maintenance Duration (per occurrence, in year) |
| CB         | 0.07                           | 0.0005                          | 0.5                           | 0.0001                       |
| Cable      | 0.068/km/yr                    | 0.0006                          | 0.014/km/yr                   | 0.0002                       |
| Transformer| 0.07                           | 0.0007                          | –                             | –                            |
| Busbar     | 0.05                           | 0.0005                          | 0.2                           | 0.0001                       |

### 3. Result and discussion

#### 3.1. Load flow analysis

**Table 3. Voltage profile.**

| Bus ID       | Radial Ring with PS-201 to PS3-AC2 | Ring with PS-201 to PS5-BG1 Disconnected |
|--------------|-----------------------------------|----------------------------------------|
| PS-201       | 1.01 pu 1.01 pu 1.00 pu 1.00 pu   | 1.00 pu                                 |
| PS5-BG1      | 1.00 pu 1.00 pu 0.98 pu 0.94 pu*a  | 0.96 pu*b                               |
| PS4-AC3      | 1.00 pu 0.99 pu 0.96 pu*a 0.95 pu*b | 0.96 pu*b                               |
| PS3-AC2      | 0.97 pu*a 0.99 pu 0.95 pu*b 0.96 pu*b |                            |

*a Marginal  
*b Critical

Voltage profile in Table 3 shows that ring configuration performs better compared to the existing radial configuration in that it improves the marginal PS3-AC2 bus into normal category. It is also expected that contingency cases perform worse than radial configuration because of their longer route and higher load.

Cable loading in Table 4 shows that all the cables are still in normal loading category for each case. The result appears as expected in that the ring generates more balanced loading [6]. The contingency cases, on the other hand, are actually radial configuration with longer route and unbalanced load so that they produce high loading in some parts of their segments.

There are marginal and critical categories in voltage profile that can be improved by upsizing cable-13 and cable-14 size from 70 mm² to 120 mm². Increasing the cable size reduces the voltage drop. In general, the recommendation raises the voltage profile by 0.01 pu. It helps several sections moving up to marginal from critical category.

#### 3.2. Short circuit analysis

In both radial and ring configurations, all devices work in normal category with the ratio between short circuit current and devices capability peaks at only 28.1%. It is as expected that ring application produces increased short circuit current because interconnection between buses creates short circuit current contribution through two directions sourced from PS-201 [7]. Yet, all devices are still able to handle that increment. Table 5 and Table 6 show the maximum value of short circuit current. They show that the increase in short circuit current in ring application is not significant.

**Table 5. Busbar maximum momentary duty.**

| Configuration | Symmetrical Current (kA) rms | Asymmetrical Current (kA) rms |
|--------------|------------------------------|------------------------------|
| Radial       | 5.508                        | 8.729                        |
| Ring         | 5.520                        | 8.747                        |

**Table 6. Circuit breaker interrupting duty.**

| Configuration | Symmetrical Current (kA) rms | Asymmetrical Current (kA) rms |
|--------------|------------------------------|------------------------------|
| Radial       | 4.842                        | 4.930                        |
| Ring         | 4.846                        | 4.934                        |
3.3. Protection relay coordination analysis
Unlike radial configuration, ring application contributing fault current comes from two directions: forward and reverse, (see Figure 4). This situation requires that feeder relay use directional type of protection [8,9], while generator relay may still use the existing, non-directional, relay.

![Diagram of forward and reverse current during a fault](image)

Figure 4. Forward and reverse current during a fault.

Table 7. New relay setting.

| Relay ID | CT Ratio | I Pick Up (sec) | Time Dial | Curve       |
|----------|----------|-----------------|-----------|-------------|
| 15       | 51N      | 50:5            | 1.5       | 24          | Short Inverse |
| 16       | 51       | 200:5           | 6.75      | 97          | Short Inverse |
| 17       | 51N      | 50:5            | 1.5       | 24          | Short Inverse |
| 18       | 51       | 200:5           | 7.5       | 94          | Short Inverse |
| 67       | 400:5    | 10.5            | 5         | Short Inverse |
| 67N      | 400:5    | 0.64            | 10.1      | Short Inverse |
| 67       | 400:5    | 4.5             | 0.5       | Short Inverse |
| 67N      | 400:5    | 0.3             | 0.5       | Short Inverse |
| 67       | 400:5    | 10.5            | 5         | Short Inverse |
| 67N      | 400:5    | 0.64            | 5.8       | Short Inverse |
| 51       | 67N      | 400:5           | 0.64      | 5.8         | Short Inverse |
| 55-R     | 67N      | 400:5           | 0.3       | 2.6         | Short Inverse |
| 55-R     | 67N      | 400:5           | 0.64      | 2.2         | Short Inverse |
| 67       | 400:5    | 7.6             | 3         | Short Inverse |
| 67N      | 400:5    | 0.5             | 5.3       | Short Inverse |
| 67       | 400:5    | 10.5            | 0.5       | Short Inverse |
| 12-R     | 67N      | 400:5           | 0.64      | 0.5         | Short Inverse |
| 19       | 67N      | 400:5           | 0.64      | 8.4         | Short Inverse |

Table 7 is the new relay setting as result of protection coordination analysis. Relay ID 15 to 18 are generator relays. They use the existing relay with higher time dial than before. While the other relay IDs are the new, directional type, feeder relay. This setting yields coordinated curves that comply with the requirements stated in methodology section.
3.4. Reliability analysis

Table 8. Outage duration.

| Load | Outage Duration (hour) | Radial | Ring | Incremental |
|------|------------------------|--------|------|-------------|
| B1   | 5.909                  | 3.287  |      | 2.622       |
| B2   | 4.207                  | 3.287  |      | 0.92        |
| B3   | 7.206                  | 3.287  |      | 3.919       |
| Total| 17.322                 | 9.861  |      | 7.461       |

Table 8 shows the outage duration to supply load B1, B2, and B3. It is expected that ring system yields better outage duration as it offers better supply continuity [10]. Outage duration in the result is provided in hour unit. It can be converted into year unit by a factor of 1/8760.

4. Conclusion

The application of ring configuration in this case study requires adjustment in the cable size and protection relay system. Load flow analysis concluded that there are buses in marginal and critical voltage profile category during contingency case. It is recommended to increase cable-13 and cable-14 size from 70 mm² to 120 mm² so that the voltage profile is improved. Meanwhile, busbar and circuit breaker short circuit rating are still able to handle ring short circuit current and thus upsizing is not required. In protection relay aspect, besides the new relay setting proposed in the result section, the application of ring configuration obliges feeder relay replacement to directional type because of forward and reverse current occurrence.

Ring configuration improves reliability by offering better supply continuity i.e. more routes are created to load side. This study evaluates that the application of ring configuration generates lower outage duration of 9.861 hours annually, as compared to 17.322 hours of the existing radial configuration. Future study is recommended to provide economic aspect of these drawbacks relative to the benefits and to improve and/or adjust the assumptions used in this study to each need. Future study is recommended to provide economic aspect of these drawbacks relative to the benefits and to improve and/or adjust the assumptions used in this study to each need.

Acknowledgments

This research was supported by Universitas Indonesia through PUTI grant 2020 (International Indexed Publication) launched by DRPM UI.

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