Overload handling of IBT using load and capacitor shedding

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Abstract. Faulted Inter Bus Transformer (IBT) can cause power system instability. Therefore, it will be isolated to prevent the spreading of disturbance. IBT at the Ptn Substation which supplies Ptn – Grt and Dwt Subsystem is discussed in this paper. The event discussed is 2 of 3 IBTs are out of work so that only one left. So, load shedding of Dwt Subsystem is required to avoid further disturbance. However, after it is applied, the voltage at the Dwt Subsystem will increase beyond the allowed rating. Therefore, further action is required by releasing some capacitor banks of several substations that have the highest rated voltage until the voltage in all substations is within the permitted rating. Finally, The system return to stable after load shedding with total 226.45 MW and capacitor shedding with total 150 Mvar.

1. Introduction
Load shedding is an action that can be chosen for handling instability in the electric power system [1, 2]. It is usually applied when instability occurs because of supply deficiency [3]. There are various types of load shedding which depend on its stability parameters, such as under-voltage load shedding (UVLS) or under-frequency load shedding (UFLS) [4]. Load shedding handling by UVLS and UFLS and its modifications have been widely studied or applied [5-8]. Furthermore, there is also overload shedding (OLS) [9, 10], which is usually applied when the standard parameter to determine to release the loads, such as the frequency and the voltage, are in a normal condition. Also, it is used when electricity demand and power generation are stable, but the existing lines or transformers have a lower rating than the power that needs to be transmitted, so that it causes them overload [9].

The Ptn substation transmits electricity to Ptn – Grt subsystem and to Dwt subsystem. Therefore, if there is a disturbance in the Ptn substation such as a trip of the IBT, then the load shedding will be first applied for Dwt subsystem since the Ptn – Grt subsystem is prioritized over Dwt subsystem.

In this study, 2 of 3 IBT of the Ptn substation are tripped. In this case, the generation (supply) and the loads (demand) are not changed, but the power cannot be transmitted due to the loss of the IBTs. This condition causes the power supplies to the loads is reduced, and if no further actions are taken then the remaining IBT will also be tripped.

Load shedding can cause voltage increasing so it can also cause some substation in Dwt to become overvoltage. Therefore, further action is needed to stabilize the voltage to its rating limit based on "Aturan Jaringan Sistem Tenaga Listrik Jawa – Madura Bali Tahun 2007" [11], where the transmission in Dwt use 150 kV with a tolerance of +5/-10%. The further action required by capacitor shedding so that the voltage will drop.

2. Load and Capacitor Shedding

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2.1. Load shedding
Load shedding is a method where there is some load released of the power system. This load shedding is applied to get a new balance between electricity demand and power generation to restore system stability. Load shedding required when there is electricity supply reduced or load increase more than power generation can cover.

\[ P_S = P_R + P_{loss} \]  
\[ P_R = VI \cos \theta \]  
\[ V = E - jXI - RI \]  

where \( P_R \) is the load (W), \( P_S \) is the power generated (W), \( P_{loss} \) is the power loss (W), \( V \) is the receiver voltage (V), \( I \) is the current flow (A), \( X \) is the line reactance (Ω), \( R \) is the line impedance (Ω), and \( E \) is the supply voltage (V).

Refer to (1), (2), and (3); the load shedding would cause the current flow to decrease. By assuming impedance lines are fixed, the current decrease at the receiver would cause the voltage drop in the line to decrease as well. So, the voltage at the system will increase.

2.2. Capacitor shedding
As seen in figure 1, the capacitor can increase the voltage value. From this concept, besides its primary function to improve the power factor by injecting reactive power to the system (4)-(7), it can also improve the voltage. So, it can be applied to a transmission line that has a voltage drop [12].

\[ i = c \frac{dv}{dt} \]  
\[ I = j \omega CV = \frac{V}{Z_C} \quad \text{when} \quad Z_C = \frac{j}{\omega C} \]  
\[ S = VI^* = V \left[ \frac{V}{Z_C} \right]^* = \frac{|V|^2}{Z_C^*} = |V|^2 [j \omega C]^* = |V|^2 [-j \omega C] \]  
\[ S = P + jQ \quad \text{where} \quad P = 0 \quad \text{and} \quad Q = -\omega C |V|^2 \]  

![Phasor diagram of capacitive load](image)

**Figure 1.** Phasor diagram of capacitive load

Capacitors are placed in the substation near the load. So, the reactive power produced by the capacitor will reduce the reactive power transmitted from the generator. Lower reactive power flow will cause the voltage to drop smaller as proven by (8)-(13).
Figure 2. Simple equivalent circuit and phasor diagram of transmission

\[ E^2 = (V + \Delta V)^2 + \delta V^2 \]  \hspace{1cm} (8)

\[ E^2 = (V + RI \cos \phi + XI \sin \phi)^2 + (XI \cos \phi - RI \sin \phi)^2 \]  \hspace{1cm} (9)

\[ E^2 = \left( V + \frac{RP}{V} + \frac{XQ}{V} \right)^2 + \left( \frac{XP}{V} - \frac{RO}{V} \right)^2 \]  \hspace{1cm} (10)

If

\[ \delta V \ll V + \Delta V \]  \hspace{1cm} (11)

So, \( \delta V \) can be ignored

\[ E^2 = \left( V + \frac{RP}{V} + \frac{XQ}{V} \right)^2 \]  \hspace{1cm} (12)

If \( R \) be ignored, so

\[ \Delta V = E - V = \frac{XQ}{V} \]  \hspace{1cm} (13)

Where \( E \) is the generation voltage, \( V \) is the voltage at load, \( P \) the active power at transmission, \( Q \) is the reactive power at transmission, \( X \) is the transmission reactance, and \( R \) is the resistance at the transmission.

Based on (8)-(13) and figure 2, bigger the reactive power transmitted and the inductive load on the channel than more significant voltage drop, vice versa. Conversely, the smaller the reactive power sent, the smaller the voltage drop. It can be concluded that capacitor shedding will cause voltage decrease.
3. **Simulation and Result**

This simulation uses the DIgSILENT ver. 15.1 and run in several conditions. The conditions including normal condition, unstable condition because of disturbance, a condition when load and capacitor shedding applied, and final condition when the system back to the stable.

### 3.1. Normal condition

The normal condition must be checked first to see how much change occurs in the system before and after disturbance. The data used in this paper are when peak load occurs in the power system. Peak load selected to see maximum IBT Ptn loading at a normal state as displayed in Table 1.

**Table 1. Normal condition IBT loading**

| Transformer | Apparent Power (MVA) | Loading (%) | Connection           |
|-------------|----------------------|-------------|----------------------|
| IBT1        | 299.42               | 61.12       | Connected to Bus A   |
| IBT2        | 299.42               | 61.12       | Connected to Bus A   |
| IBT3        | 329.77               | 66.07       | Connected to Bus B   |

IBT 1 and 2 loadings are the same, but they are different from IBT 3. This is because IBT 1 and 2 supply the same load and are connected parallel, while IBT 3 is different. IBT 1 and 2 are connected to the Bus A while IBT 3 is connected to Bus B. Bus A and Bus B are isolated from each other.

### 3.2. Two of Three IBTs Ptn Trip Scenario

The scenario used to symbolize disturbance by releasing 2 of 3 IBTs Ptn of the system. There is no certainty which IBT will trip. Therefore, analysis is needed to determine the new configuration of IBT and the transmission line connected to it to minimize the overload of the remaining IBT and optimize power supplies from other sources.

**Table 2. IBT Ptn configuration possibilities when disturbance occurs**

| Connected to (Ptn Substation Bus) | Loading (%) | Adjective             |
|-----------------------------------|-------------|-----------------------|
| Bus A                             | 133.98 %    | No change             |
| Bus B                             | 99.96 %     | No change             |
| Bus A and B                       | 165.91 %    | Bus A and B connected |

Refer to Table 2; the best configuration is when 1 IBT left is connected to Bus B only. However, that configuration cannot be applied because Bus A would not get supply from IBT Ptn while Bus A is the bus that connects IBT Ptn and Dwt Subsystem. If Bus A does not get any supply, Dwt Subsystem will lose almost all its additional supply.

So, the best configuration is selected when 1 IBT left connected to Bus A only because the loading will not as much as while it connected to both buses. Another reason because bus B that connected to several substations in Ptn – Grt Subsystem, that substations still have another supply that will make them still in a stable state even without supply from IBT Ptn.

### 3.3. Load Shedding of Dwt Subsystem

Load shedding required to make IBT loading is no longer overload when a disturbance occurs and cause only 1 IBT that still online. Before load shedding applied, knowing the load profile is so important to make sure which load would be released of the system. The first load would be released of the system are the smallest load. Because there is no certainty which load with similar value is the biggest or the smallest one when a disturbance occurs, their value is considered the same and that load grouped into several groups. Each group is distinguished by the amount of the load, as seen in Table 3.
Table 3. Load grouping

| Group of load | Name | Act. Power (MW) | Total Power (MW) |
|---------------|------|----------------|------------------|
|               | A    | 5.144685       |                  |
|               | B    | 5.361556       |                  |
|               | C    | 6.156754       |                  |
| 0 – 10 MW     | D    | 6.506162       | 49.314273        |
|               | E    | 7.518227       |                  |
|               | F    | 8.855607       |                  |
|               | G    | 9.771282       |                  |
|               | H    | 10.56648       |                  |
|               | I    | 11.18096       |                  |
|               | J    | 12.96411       |                  |
|               | K    | 13.38582       |                  |
| 10 – 20 MW    | L    | 14.78345       | 113.59275        |
|               | M    | 15.69913       |                  |
|               | N    | 17.41001       |                  |
|               | O    | 17.60279       |                  |
|               | P    | 20.14501       |                  |
|               | Q    | 21.20526       |                  |
|               | R    | 21.55466       |                  |
|               | S    | 21.84383       |                  |
|               | T    | 25.50654       |                  |
| 20 – 30 MW    | U    | 26.16923       | 247.02923        |
|               | V    | 26.77164       |                  |
|               | W    | 27.51865       |                  |
|               | X    | 27.94034       |                  |
|               | Y    | 28.37407       |                  |

After load being grouped, the next step is load shedding. The load that is released at this stage are all load in each group, starting with the group that has the smallest to the biggest load until IBT does not overload anymore. The first one being released is the smallest one to make the amount of load being released of the system as minimum as possible.

Table 4. Load shedding first stage

| Load Shedding Stage | Accumulative Load Shedding (MW) | IBT Loading |
|---------------------|---------------------------------|-------------|
| Before Load Shedding| 0                               | 133.98 %    |
| 0-10 MW             | 49.314273                       | 125.42 %    |
| 10-20 MW            | 162.907023                      | 107.99 %    |
| 20-30 MW            | 409.936253                      | 76.38 %     |

At 20-30 MW load shedding stage, it is shown in table 4 that IBT loading 76.38 %. To minimize the amount of load shedding, load from 20-30 MW group are selected which would be released or not. Before load shedding applied, the load is shorted by the impact to the voltage average in Dwt Subsystem to minimalize increasing of voltage in Dwt Subsystem. Because there are many substations in Dwt Subsystem, load shedding impact to voltage calculation is determined in (14).
\[ \Delta V_X = \frac{\sum L S_i V_{LSi} - V_0}{n} \]  

(14)

Where \( \Delta V_X \) is the average voltage (kV), \( V_{LSi} \) is the voltage after load shedding (kV), \( V_0 \) is the voltage before load shedding (kV), and \( n \) is the total of the substation.

Table 5. Impact by load shedding to the voltage change of 20-30 MW group

| Name | Act. Power (MW) | Average Voltage Increase (kV) | Sequence |
|------|----------------|-------------------------------|----------|
| P    | 20.14501       | 2.9901                        | 2        |
| Q    | 21.20526       | 3.1172                        | 4        |
| R    | 21.55466       | 2.4132                        | 1        |
| S    | 21.84383       | 3.0083                        | 3        |
| T    | 25.50654       | 3.7081                        | 7        |
| U    | 26.16923       | 3.6322                        | 6        |
| V    | 26.77164       | 3.3226                        | 5        |
| W    | 27.51865       | 3.9265                        | 9        |
| X    | 27.94034       | 3.9050                        | 8        |
| Y    | 28.37407       | 4.0238                        | 10       |

After the sequence is known, load shedding is applied one by one (can be seen in Table 5) by starting with the load which has the smallest impact on voltage change until IBT Ptn does not overload anymore as seen in Table 6.

Table 6. Load shedding final stage

| No of stage | Load Shedding | Load value (MW) | IBT Loading (%) | Act. Power (MW) | Apparent Power (MVA) |
|-------------|---------------|----------------|-----------------|-----------------|---------------------|
| 0           | At disturbance| 0              | 133.98 %        | 641.61          | 661.61              |
| 1           | 0-10 MW       | 49.314273      | 125.42 %        | 606.24          | 619.80              |
| 2           | 10-20 MW      | 113.59275      | 107.99 %        | 529.68          | 534.39              |
| 3           | R             | 21.55466       | 104.88 %        | 515.50          | 519.10              |
| 4           | P             | 20.14501       | 102.10 %        | 502.68          | 505.47              |
| 5           | S             | 21.84383       | 98.97 %         | 488.02          | 490.04              |
| 6           | Q             | 21.20526       | 96.16 %         | 474.75          | 476.22              |

TOTAL LOAD SHEDDING 247.655783

CHANGES IN IBT 37.82 % 166.66 185.39

As shown in Table 6, at the 5th stage, the IBT is no longer overload, but because it is still very close to the maximum limit of IBT capacity 500 MVA and also because when the load is released the swing occurs due to a transient change to find a new balance. So, the IBT loading is still above 100% as shown in Figure 3. Therefore, one more load should be released.
3.4. Capacitor shedding of Dwt subsystem

Load shedding will cause voltage in the system increase, and at some point, it can become overvoltage. At that case, capacitor shedding is needed to make voltage back to normal again. After load shedding of Dwt Subsystem, most buses voltage are over their permitted limit while the limit for transmission voltage in Dwt Subsystem is -10%, +5% or between 135 to 157.5 kV and the voltage rating 150 kV. The voltage after load shedding of Dwt Subsystem is shown in Table 7.

| Substation | Voltage (kV) | Voltage (p.u.) | Adjective |
|------------|--------------|----------------|-----------|
| AA         | 160.71       | 107.14%        | Critical  |
| BB         | 158.41       | 105.61%        | Critical  |
| CC         | 159.35       | 106.23%        | Critical  |
| DD         | 160.71       | 107.14%        | Critical  |
| EE         | 152.77       | 101.85%        | Normal    |
| FF         | 161.26       | 107.51%        | Critical  |
| GG         | 159.94       | 106.63%        | Critical  |
| HH         | 155.44       | 103.63%        | Normal    |
| II         | 161.32       | 107.55%        | Critical  |
| JJ         | 160.54       | 107.03%        | Critical  |
| KK         | 159.1        | 106.07%        | Critical  |
| LL         | 159.29       | 106.19%        | Critical  |
| MM         | 160.58       | 107.05%        | Critical  |
| NN         | 160.66       | 107.11%        | Critical  |
| OO         | 160.66       | 107.11%        | Critical  |
| PP         | 160.61       | 107.07%        | Critical  |
| QQ         | 160.96       | 107.31%        | Critical  |
Before capacitor shedding applied, needed to know which capacitor will be shedding and which ones are not by shorting capacitor with how much influence it has to voltage change in the system. The capacitor that has the biggest impact will release from the system first to minimalize the total amount of capacitors being released.

There is two types of the capacitor by its capacity, which is the 25 Mvar and 50 Mvar. The 50 Mvar capacitor, of course, has a bigger impact on the voltage system than 25 Mvar. So, the 50 Mvar capacitors will be released first. Because there are five 50 Mvar-capacitors that active, they will be shorted first to make sure the sequence of capacitor shedding until Dwt Subsystem no longer overvoltage. The formula to calculate the impact of capacitor shedding to voltage decline is determined in Equation (15).

\[
\Delta V_X = \frac{\sum_{i=1}^{n} V_0 - V_{CSI}}{n}
\]

(15)

Where \(\Delta V_X\) is the average voltage (kV), \(V_{CSI}\) is the voltage after capacitor shedding (kV), \(V_0\) is the voltage before capacitor shedding (kV), and \(n\) is the total of the substation.

| Name  | Reactive Power (Mvar) | Average Voltage Decreasing (kV) | Sequence |
|-------|-----------------------|---------------------------------|----------|
| CAP_1 | 50                    | 5.0353                          | 4        |
| CAP_2 | 50                    | 4.7525                          | 5        |
| CAP_3 | 50                    | 5.2594                          | 1        |
| CAP_4 | 50                    | 5.0525                          | 3        |
| CAP_5 | 50                    | 5.1763                          | 2        |

After the sequence is known as shown in table 8, capacitor shedding is applied one by one starting with the capacitor which had the biggest impact on voltage change until the voltage in Dwt Subsystem no longer overvoltage.

| Substation | Voltage (kV) | 1st Stage | 2nd Stage | 3rd Stage |
|------------|--------------|-----------|-----------|-----------|
| After Load shedding | 158.61 | 156.6 | 154.54 | |
| AA | 158.41 | 156.6 | 154.9 | 153.05 |
| BB | 159.35 | 157.56 | 155.86 | 154.01 |
| CC | 160.71 | 158.61 | 156.6 | 154.54 |
| DD | 152.77 | 151.75 | 150.78 | 149.72 |
| EE | 161.26 | 158.08 | 155.99 | 153.82 |
| FF | 159.94 | 157.91 | 155.99 | 153.91 |
| GG | 155.44 | 154.06 | 152.76 | 151.34 |
| HH | 161.32 | 157.77 | 155.67 | 153.55 |
| II | 160.54 | 158.39 | 156.36 | 154.13 |
| JJ | 159.1 | 157.19 | 155.38 | 153.42 |
| KK | 159.29 | 157.61 | 156.02 | 154.29 |
| LL | 160.58 | 158.39 | 156.35 | 154.06 |
| MM | 160.66 | 158.52 | 156.41 | 154.41 |
| NN | 160.66 | 158.52 | 156.41 | 154.41 |
| OO | 160.61 | 158.93 | 157.33 | 155.58 |
| PP | 160.96 | 158.83 | 156.74 | 154.72 |
| Capacitor Shedding Cumulative (Mvar) | 50 | 100 | 150 | |
At the 2nd stage of capacitor shedding, the voltage in all substations are at their normal level. However, some substations have a voltage level that still too close to that permissible limit such as PP Substation that has voltage 157.33 kV where the upper threshold is 157.5 kV. Because this paper use load when peak time, It will have a chance when the load is not as high as in this data, and it would cause the voltage to become higher than Table 9 shown. Besides that, the closer voltage to the rating voltage of 150 kV is better. Therefore, one more capacitor should be released.

3.5. IBT Loading Profile after Load and Capacitors Shedding

After load shedding applied, the power needed by the load is reduced. So, the active and reactive power flow at IBT is decreased. Then, the capacitors shedding causes some of the reactive power supplied by the capacitor disappear and compensated by the reactive power from IBT. Therefore, the reactive power at IBT increases.

Moreover, the active power decreases after capacitor shedding because the voltage in the Dwt Subsystem decreases. Based on Ohm's Law, if the voltage decrease and the resistance at the load are considered constant, the current will decrease as well. So, it will result active power flow also decrease.

| Condition After | Disturbance | Load Shedding | Capacitor Shedding |
|-----------------|-------------|---------------|--------------------|
| Apparent Power (MVA) | 661.61 | 476.22 | 465.43 |
| Active Power (MW) | 641.61 | 474.75 | 462.3 |
| Reactive Power (Mvar) | 161.43 | 37.32 | 53.93 |

As shown in table 10, The IBT loading decrease causes the load shedding can slightly be reduced. After repeated simulations. 6th stage of load shedding can be canceled. So, the final of load shedding, capacitor shedding, and some other parameters can be seen in Table 11-12.

| Load Shedding Total | 226.450523 | MW |
| Capacitor Shedding Total | 150 Mvar |
| Apparent Power in IBT (MVA) | 479.38 | MVA |
| Active Power in IBT (MW) | 475.49 | MW |
| Reactive Power in IBT (Mvar) | 60.95 | Mvar |

**Table 12.** Final voltage in all Dwt Substation after 6th stage of load shedding is canceled

| Substation | Voltage (kV) | Adjective | Substation | Voltage (kV) | Adjective |
|------------|--------------|-----------|------------|--------------|-----------|
| AA         | 153.88       | Normal    | JJ         | 153.47       | Normal    |
| BB         | 152.41       | Normal    | KK         | 152.77       | Normal    |
| CC         | 153.37       | Normal    | LL         | 153.67       | Normal    |
| DD         | 153.88       | Normal    | MM         | 153.39       | Normal    |
| EE         | 149.28       | Normal    | NN         | 153.79       | Normal    |
| FF         | 152.87       | Normal    | OO         | 153.8        | Normal    |
| GG         | 153.24       | Normal    | PP         | 154.92       | Normal    |
| HH         | 150.79       | Normal    | QQ         | 154.08       | Normal    |
| II         | 152.7        | Normal    | **Voltage Average** | **153.08** | **Normal** |
4. Conclusion
The trip of 2 of 3 IBTs at Ptn Substation result in overload of the last remaining IBT. Hence, it is required to release some of loads of Dwt subsystem, with consider voltage change to minimize over voltage. IBT are no longer over load after load shedding with total 226.45 MW. The load shedding causes the voltage at Dwt Subsystem increase beyond the allowable limit. So, the capacitor shedding of Dwt Subsystem is required, with the greatest influence to the voltage change is selected first. The system is no longer overvoltage after capacitor shedding with total 150 Mvar.

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