Transient stability study of the Hsin Yu Co-Generation Plant in Hsin-Chu Science Based Industrial Park in Taiwan

Werner S. Zimmermann  Stefan Hopp  Michael Bondeur
Electric Systems Consulting
ABB Calor Emag Schaltanlagen AG
Mannheim Germany

Der-Nien Chen
Technical Department
Hsin Yu Energy Development Co., LTD
Taipei, Taiwan

Abstract: A transient stability study of the Hsin Yu Co-Generation (HYC) plant in Hsin-Chu Science Based Industrial Park in Taiwan for different operation modes was carried out. The combined cycle plant consists of three gas-turbine generators and one steam-turbine generator. The total generating capacity is 215 MVA. The plant feeds via two 161/161 kV transformers into the 161 kV TPC (Taiwan Power Company, Taipower) network. The loads fed from the internal 161 kV and 22.8 kV busbars amounts 145 MW. So dependent from the actual load/generation conditions, both a large power export as well as a large power import is possible.

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I. SINGLE LINE DIAGRAM OF THE PLANT

Fig. 1 shows a single line diagram of the plant. The supplying 161 kV bus Long-Sung is also indicated.

II. METHODOLOGY

The behaviour of the HYC power system in case of power station outages in the TPC network, near and remote short-
circuits is simulated with a powerful transient stability program. The influence of unit exciter systems, speed governors and dynamic load behaviour is taken into account.

The network calculation program CALPOS® by ABB includes all necessary tools to calculate transient stability cases. The CALPOS® load flow module performs the load flow calculation necessary as input for the transient analysis. The CALPOS® module dynamic stability determines the transient stability results.
1) Network under study: The HYC plant is modeled explicitly down to the 0.48 kV-bus including a detailed model of all generators and ac-motors.

The directly connected Taipower 161 kV-network group including the neighboring power station is exactly modeled. The generators of the power station are represented in detail.

The complete Taipower 345 kV -network was explicitly modeled in a separate step and subjected to a specific network reduction. The reduced network shows the identical electrical behaviour in terms of fault level and load flow as the original Taipower network. Moreover, the complete Taipower network was modeled and reduced for peak load and off-peak load condition in the network and considered in the study at different operation modes. Point of intersection between detailed network model and reduced network model is the neighbouring power station.

2) Synchronous machines: Using CALPOS® the machines are represented by a detailed model. The generators are represented by a sub-transient standard model with two rotor windings in the d-axis and one in the q-axis. The model also considers the machine saturation. The equivalent generators representing the dynamic network model of the reduced Taipower network are modeled on the base of the subtransient generator data taken from [1].

3) Voltage controller and excitation system: The voltage and excitation system of the HYC generators are modeled in detail using block structures according to the manufacturer’s data.

The voltage and excitation system of the TPC generators are modeled using the standard IEEE format as described in [2] for a simplified voltage controller system. All generators and exciters have been tested to check their unique system behaviour. The answer of the excitation system to a step of the reference voltage of 5 % is checked for a reasonable response.

4) Turbine controller and governor system: The turbine controller and governor system of the HYC generators and the neighbouring power station are modeled in detail according to the manufacturer’s data.

The turbine controller and governor system of the equivalent generators of the Taipower network are modeled applying several first-order lag functions with adequate limits to establish the spinning reserve available in the power system. The governor tests showed for each case a positive and stable system behaviour with a good and sufficient damping.

5) Load model for dynamic and static loads: The dynamic loads such as asynchronous machines are modeled using the T-equivalent circuit with a slip dependent rotor resistance gained through analysis of the torque/speed-, current/speed- and power factor/speed-relationship of each individual motor combined with their inertia constant. The model gives the correct behaviour of the voltage and frequency dependency of the asynchronous machines.

The static load model bases on the so-called ZIP load model to meet the frequency and voltage dependency of the loads. The ZIP model is composed of constant impedance (Z), constant current (I), and constant power (P) portion. The frequency dependency is considered by a slope $\delta P/\delta f$ respective $\delta Q/\delta f$. The determined load parameters are based on sample characteristics of different load classes taken from [3].

6) Load flow base cases: To cover all influences on the behaviour of the HYC plant caused by external and internal faults it was agreed to study 12 different operation modes of the HYC plant. Table 1 gives an overview on the operation modes under study with the related plant generation and plant consumption modes.

### Table 1: Plant Operation Modes.

<table>
<thead>
<tr>
<th>Oper. mode</th>
<th>Load#1</th>
<th>Load#2</th>
<th>Load#3</th>
<th>Load#4</th>
<th>Gener. MW</th>
<th>TPC Load condition</th>
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<tbody>
<tr>
<td>22.8 kV</td>
<td>11</td>
<td>11</td>
<td>30</td>
<td>15</td>
<td>103.46</td>
<td>peak</td>
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<td>161 kV</td>
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<td>45</td>
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<td>45</td>
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<tr>
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<td>45</td>
<td>30</td>
<td>103.46</td>
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<tr>
<td>34</td>
<td>34</td>
<td>34</td>
<td>45</td>
<td>30</td>
<td>48.68</td>
<td>off-peak</td>
</tr>
<tr>
<td>34</td>
<td>34</td>
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<td>45</td>
<td>30</td>
<td>48.68</td>
<td>off-peak</td>
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<tr>
<td>34</td>
<td>34</td>
<td>34</td>
<td>45</td>
<td>30</td>
<td>44.98</td>
<td>peak</td>
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<tr>
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<td>22</td>
<td>22</td>
<td>45</td>
<td>30</td>
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<td>161 kV</td>
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<td>34</td>
<td>45</td>
<td>30</td>
<td>0</td>
<td>peak</td>
</tr>
</tbody>
</table>

### III. CRITICAL CLEARING TIME

The critical clearing time (cct) is defined as the maximum time between initiation of a three-phase fault and the last-pole current clearing of the fault leading to stable conditions in the network. Compared with the tripping time for existing or proposed protection devices and circuit breaker equipment the cct-study may lead to recommendations for improvements or underline that the given settings are sufficient. Fig. 2 shows exemplary a simulation of a 3-phase s/c with a fault duration time close to the cct. The fault occurs at $t=0.1s$ and is removed at $t=0.3s$. The rotor angles of the generators accelerate to 160° and come back to a stable operation point. The steam turbine generator reaches a maximum rotor angle of 60°.

Aim of this part of the study is to determine the relation between voltage drop at the MOF due to external disturbances and generator stability. This relation "critical clearing time as function of the voltage at the MOF" is an important design criterion for the setting of the under-voltage relay of the de-coupling scheme.
In order to calculate a steady relation between voltage and the critical clearing time the voltage drop was created with artificial 3p-short-circuits applied with an increasing fault reactance. The calculations were carried out for all operation modes. Fig. 3 summarises the results of the calculations representing the cct as a function of the voltage at the 161 kV Bus #2 (MOF).

IV. STABILITY ANALYSIS OF HYC INTERNAL FAULTS

Different internal fault cases have been simulated. The results are used to examine the general dynamic behaviour of the plant and to find the adequate settings or to confirm the given settings of the in-plant protection system. Severe faults like 161 kV bus faults, 13.8 kV bus faults, faults within transformer protection zones have been performed. The operation of the protection system which is activated by the fault is considered in the study.

Summarised the following conclusions can be drawn:
- Most important for the stability of the HYC generators is the fault location and the pre-fault operation point of the generators. Faults near the 13.8 kV generator busbars with the concerned generator operating at rated active power yields the shortest cct. For normal operation:
  - Shortest cct of the gas-turbine generators: 155 ms
  - Shortest cct of the steam-turbine generator: 265 ms
- The influence of the TPC network loading condition (peak load or off-peak load) on the cct is minor.
- Faults at 22 kV or 3.3 kV voltage levels do not lead to generator instability

V. STABILITY ANALYSIS OF HYC EXTERNAL FAULTS

Different external fault cases have been simulated. The results are used to find adequate settings for the undervoltage path of the de-coupling scheme. Severe faults like bus faults of external 345 kV, 161 kV, 69 kV busses, bus outages and close line faults have been performed. Expected tripping functions of the external protection system caused by the fault are also considered.

Summarised the following conclusions can be drawn:
- 161 kV bus faults respectively faults at outgoing lines for a fault-duration of 0.1 s do not lead to generator instability. A fault duration of 0.4 s exceeds the critical clearing time at this fault location - all gas turbine generators loose their stable operation, the steam turbine generator returns to stable operation after a pole slipping of 360 degrees. But steam turbine generator will trip because there is no exhaust from gas turbine.
- The critical clearing time for a short circuit close to the 161 kV bus #2 (MOF) is 200 ms. Depending on the fault location respectively the fault impedance the cct will range from 200 ms to 695 ms. Line faults cleared within 0.2 s will not cause HYC generator instability – but, if the fault location is close to the HYC plant the generators approach their stability limit.
- 69 kV faults near to the HYC plant with fault clearing times below 400 ms do not affect the HYC generators distinctly.
- 345 kV line faults do not cause generator instability when they are tripped within 100 ms. A fault clearing time of 400 ms
causes instability of the gas-turbine generators. The steam-turbine generator of the plant remains stable. But steam turbine generator will trip because there is no exhaust from gas turbine.

- A bus fault at the adjacent power station followed by an outage of the station does not affect the HYC plant generators distinctly due to the large line impedance's between the two stations.

VI. STABILITY ANALYSIS OF HYC ISLAND OPERATION

The frequency decay in the HYC network due to external disturbances with and without prior short-circuit has been simulated. The results as well as the determined critical clearing times are necessary to find adequate settings for the de-coupling scheme. The negotiated case is the outage of the neighbouring 161 kV bus feeding the HYC loop. The outage of this bus results in an undefined island group of the HYC network and external loads.

The examined pre-fault power import of the HYC network is 100 MW, the external loads sums up to 115 MW. The running generation in the HYC plant is provided by one GT-Generator and one ST-Generator with a total power output of 48.7 MW. The frequency/voltage relay at the MOF senses the frequency decay or the voltage collapse due to s/c and initiates a trip in order to isolate the HYC network from the external network to create a defined HYC plant island operation. In total the agreed load shedding range after isolation is 100 MW. The HYC generation provides spinning reserve according to the agreed generation dispatch.

1) Automatic load shedding scheme: Different frequency settings and automatic load shedding schemes were taken into consideration. The following scenario is presented exemplary:

De-coupling at: 58.8 Hz, total relay time delay 50ms for de-coupling and all load-shedding stages
1. load shed. step at 58.5 Hz shed 30 MW with 50 ms
2. load shed. step at 58.2 Hz shed 40 MW with 50 ms
3. load shed. step at 57.9 Hz shed 30 MW with 50 ms

2) Outage of Long-Sung with and without prior short-circuit:
The limits of the frequency and voltage caused by the simulated outage of the feeding station in the HYC network have been determined. For simulations with prior s/c the low-stage of the under-voltage path of the de-coupling scheme with an effective time delay of 50 ms is considered.

Fig. 4 shows the frequency and voltage versus time relationship during a simulated load shedding with the above mentioned load shedding steps. Cause of the de-coupling at 58.8 Hz was a precede outage of the 161 kV bus Long-Sung without a prior bus fault.

Fig. 5 shows the current at MOF towards TPC network during faults at Long-Sung with and without prior short circuit.

Fig. 6 shows the frequency and voltage versus time relationship during a simulated load shedding with the above mentioned load shedding steps. Cause of the de-coupling was undervoltage due to a bus fault at 161 kV bus Long-Sung.

The simulations show a frequency drop to 56.9 Hz with a fast frequency recovery and a maximum frequency overshoot to 61.7 Hz. The time span of a rotor frequency below 58 Hz is less than 1 s. An analysis showed that no considerable lifetime reduction of the turbine system occurs; the generator and turbine protection system has to be co-ordinated accordingly.
Fig. 6: Frequency and voltage of the plant during load shedding with S/C.

Table 2 shows an extract of the results.

Table 2. Voltage and frequency limits during fault.
(Outage of Long-Sung)

<table>
<thead>
<tr>
<th>Value</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency 161 kV bus #2</td>
<td>57.2 Hz 1)</td>
<td>61.6 Hz 1)</td>
<td>without s/c</td>
</tr>
<tr>
<td>Voltage 161 kV bus #2</td>
<td>0.63 pu 1)</td>
<td>1.13 pu 1)</td>
<td>without s/c</td>
</tr>
<tr>
<td>Current at MOF -&gt; TPC</td>
<td>305 A 2)</td>
<td>305 A 2)</td>
<td>without s/c</td>
</tr>
<tr>
<td>Frequency 161 kV bus #2</td>
<td>56.9 Hz 3)</td>
<td>61.7 Hz 3)</td>
<td>with s/c</td>
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<tr>
<td>Voltage 161 kV bus #2</td>
<td>0.002 pu 3)</td>
<td>1.16 pu 3)</td>
<td>with s/c</td>
</tr>
<tr>
<td>Current at MOF -&gt; TPC</td>
<td>983 A 3)</td>
<td>983 A 3)</td>
<td>with s/c</td>
</tr>
</tbody>
</table>

1) see fig. 4  2) see fig. 5  3) see fig. 6

VII. DE-COUPLED SETTINGS

1) Under-voltage settings: Fig. 3 also shows the proposed setting of the under-voltage de-coupling. Input signal is the voltage at the MOF. The function consists of a three-stage under-voltage relay with following proposed settings:

Under-voltage stage 1:

U < 30% of the nominal voltage
De-coupling time = 100 ms (total relay operating time).

The time delay of 100 ms leads to an islanding operation mode approx. 150 ms after the fault entry considering a total breaker time of 50 ms. This leaves a safety margin of 50 ms towards the minimum cct for external faults of 200 ms – unfortunately the time span between permissible cct and necessary operation of the de-coupling scheme is already very close.

Under-voltage stage 2:

U < 50% of the nominal voltage
De-coupling time = 200 ms (total relay operating time).

The time delay of 200 ms allows a selective fault clearing by pilot-wire supported protection devices in the 345 kV network.

Under-voltage stage 3:

The setting of stage 3 has to be co-ordinated with the under-voltage protection of the generator and ac-motors in the HYC plant in order to avoid an internal trip of important auxiliary motors and the consequently loss of HYC generation due to an external under-voltage.

2) Under-frequency setting: The island transfer of the HYC plant due to under-frequency was studied for a de-coupling setting of 59.2 and 58.8 Hz with a total relay time delay of 50 ms. The scheme worked satisfactorily for a setting of 58.8 Hz in combination with the automatic load shedding scheme under worst conditions at 100 MW power import and 115 MW additional external load connected to the HYC plant prior de-coupling due to remote TPC station outage.

The operation of the HYC plant within an undefined island as result of an external outage without prior short-circuit does not activate the directional over-current at the MOF as the pure load current is too low. Therefore it is recommended that under-frequency trip is not linked with the directional over-current relay at the MOF.

3) Current release setting of the under-voltage path: The de-coupling is only active when the current flow at the MOF is in direction of the external network and the current value exceeds a pre-set value.

The current setting has to consider the maximum power export of the HYC plant and has to account for an increase in the current flow due to a possible outage of the largest HYC consumer. The maximum outgoing current is 310 A considering the outage of the largest consumer in the HYC plant. The minimum 2p-s/c current at the MOF of the HYC plant with only one GTG in service is 440 A – therefore a current setting of 400 A is considered sufficient to detect the minimum s/c-current under worst conditions.

Fig. 7 shows the proposed de-coupling scheme with the recommended settings.

VIII. ANALYSIS OF THE DE-COUPLED SETTINGS

Different external fault cases have been studied, taking the recommended de-coupling scheme into account. Aim of the analysis was to proof the expected behaviour – secure islanding of the HYC plant in case of stability endangering faults and on the other side, remaining at the TPC network in case of faults which do not jeopardise the HYC plant stability.

Therefore the minimum bus voltage at the MOF, the maximum current at the MOF, the minimum frequency in the HYC plant...
and the maximum value of the pole angle as an indication for the stability margin was checked for different fault scenarios.

![Diagram showing settings of de-coupling scheme](image)

The examination shows that all fault cases which are endangering the HYC plant's system stability are detected by the proposed de-coupling logic as the bus voltage is below 30% respectively 50% of the nominal value and the current flow at the MOF exceeds 400 A towards TPC network.

In none of the examined cases the proposed frequency setting of 58.8 Hz at the MOF (161 kV -bus # 2) is activated. The frequency setting is low enough to stabilise it against the transient frequency drops due to the heavy short-circuits and the subsequent frequency oscillations.

The cases which do not activate the de-coupling scheme with a setting of 50% of the nominal voltage do not endanger the HYC system stability – therefore de-coupling is not necessary.

IX. SUMMARY

- The cct for faults directly at the MOF of the HYC plant is 200 ms. Remote external faults in the 161 kV TPC network which are cleared within 200 ms do not cause unstable generator operation – but the HYC generators may approach their stability limit depending on the specific fault case. Faults close to the 22 kV- and 3.3 kV- busbar does not lead to a generator instability. The influence of the TPC network loading condition (peak load or off-peak load) on the cct is minor.

- It is proposed to set the low-stage of the under-voltage path of the de-coupling scheme to 30% under-voltage at 100 ms total relay time delay and 50% under-voltage at 200 ms total time delay to ensure the islanding of the HYC plant before the stability limit of the HYC generator is approached. This stage is enabled by the directional current relay at the MOF.

- It is proposed to set the high-stage of the under-voltage path of the de-coupling scheme to approx. 80% of the nominal voltage at the MOF. The voltage setting and the time delay has to be co-ordinated with the under-voltage protection of the generator and ac-motors in the HYC plant in order to avoid an internal trip of important auxiliary motors and the consequently loss of HYC generation due to an external under-voltage. This stage is enabled by the directional current relay at the MOF.

- The setting of the current release has to be chosen according to the supposed maximum power export of the HYC plant considering a coincidental trip off large consumer in the HYC plant during a power export period. On the other hand the current release setting has to detect the minimum s/c-circuit at the MOF – a current setting of 400 A appears as a reasonable value.

- It is proposed to set the under-frequency path to 58.8 Hz with an effective total relay time delay of 50 ms to achieve island operation of the HYC plant under defined conditions.

- The automatic load shedding (ALS) scheme studied and described in V. produces a reasonable system response with a maximum frequency drop to 56.9 Hz and a fast frequency recovery to values above 58 Hz – the studied scheme can be used as a design guideline for a more refined ALS scheme.

X. REFERENCES


XI. BIOGRAPHIES

W. S. Zimmermann received the Dipl.-Ing. degree in electrical engineering in 1971 from the Technical University of Darmstadt, Germany. He worked at Brown Boveri & Cie. AG on System Planning for Public Utilities and Industrial Networks. He is currently head of section System Studies and Network Planning in the Department Electric Systems Consulting at ABB Calor Emag Schaltanlagen AG, Germany.

S. Hopp received the Dipl.-Ing. degree in electrical engineering in 1997 from the Technical University of Darmstadt, Germany and is presently project engineer in the department Electric Systems Consulting at ABB Calor Emag Schaltanlagen AG, Germany specialised in power system study and design, power system stability and protection.

M. Bondeur received the Dipl.-Ing. degree in electrical engineering in 1990 from the Technical University of Darmstadt, Germany and is presently a project engineer in the department Electric Systems Consulting at ABB Calor Emag Schaltanlagen AG, Germany specialised in power system study and design, power system stability and protection.

D. N. Chen received the MS degree in electrical engineering, majoring in power system analysis, in 1991 from Tatung Institute of Technology, Taipei, Taiwan. He is currently an electrical engineer of Hsin Yu Energy Development Co., Ltd. and involved the power system engineering and construction of Hsin-Chu cogeneration plant from the beginning.