Abstract - This paper is describing a case study on a plant-wide stability control system, which utilizes load shedding for active switching of non-essential load within milliseconds in case of an external grid power failure, in a petrochemical plant in Shanghai, China. Control philosophy and system configuration are introduced in details. Finally system limitations are examined based on actual operation of the system, and then potential improvements in the stability control system by adopting a more advanced power management system are proposed. This paper is one of the first comprehensive studies on stability control systems in industrial complexes in China.

Index Terms — Industrial grid, Stability control system, Stability control philosophy, Power management system.

I. INTRODUCTION

Stability control systems have been widely applied in most of China’s utility power grids, but few are implemented in industrial power grids due to different standards and special system requirements. For a typical petrochemical plant running on both own in-house generation and imported power from utility power grid, any accident or trip occurring on the utility power grid may immediately lead to the insufficiency of power generation. As a result, the production process could be affected or even completely shut down, which causes production loss, equipment damage, as well as safety risks, by mishandling of numerous explosive, flammable and toxic materials used in the petrochemical plants. Therefore, a petrochemical company located in Shanghai, China, has adopted a stability control system to improve the reliability of the plant [1].

II. PROBLEM DESCRIPTION

The plant grid has traditionally been self-sustainable in providing power, but due to China government’s environment and energy saving policy, power plant 1 (oil-fired) has been put out of usage, and only power plant 2 (coal-fired) is used as the sole means of in-house power generation. Consequently, the plant grid is only partially sustainable by its in-house generation, and a maximum 230MW of power gap is equivalent to half of the peak power load consumed.

After decommissioning of generation sets in power plant 1, the plant grid will be shown in Figure 1. The plant grid has three sets of 220kV power substations, which form a delta network with four loops of bus bar connections. The plant grid has two ties to Shanghai utility power.

The potential challenges with electrical power stability which the plant faces include:

1) Both ties to grid are disconnected leading to an island-mode operation, when:
   a. accidental tripping of both tie circuit breakers;
   b. tripping of one tie circuit breaker when the other is in maintenance;
2) Fluctuations of power flow due to disturbance on Shanghai utility power grid, such as:
   a. Sudden increase of the power export to utility power grid;
   b. Sudden decrease of the power import from utility power grid;
   c. Sudden reversal of the power flow direction from import to export;

III. STABILITY CONTROL PHILOPOPHY

A. Objective

The objective of a plant-wide stability control system is to protect the grid from voltage sags and/or frequency decline, under the above circumstances. In petrochemical plant grids, motors normally could sustain a 10% drop in bus bar voltage, and motor re-starting in batches could be enabled with a 15% drop in bus bar voltage. Furthermore, with presence of a greater number of generators, forced excitation will activate a more reactive power generation, which withstands the further voltage sags in a short period of time. Taking into consideration of the above characteristics of a petrochemical plant grid, the stability control system should be designed to respond to frequency decline. To halt the frequency decline and...
maintain it at a nominal value, the stability control system shall shed certain amount of loads according to the gap between available power and consumption. In another words, load shedding is key function of a stability control system.

B. Load Shedding Criteria

During the design of the stability control system, study has been done on several parameters to be used as criteria for initiation of load shedding. A selection of the parameters is given below:

1) Circuit breaker position: This signal is able to reflect disconnection of the external and internal grids, but there is the possibility that the auxiliary contacts fail to act, which causes the stability control system blind to the actual situation. Hence this criterion should be used in conjunction with other conditions for load shedding.

2) Protection relay operation: Signal is able to reflect disconnection of the external and internal grids, but there is the possibility that the relays fail to act, which causes the stability control system blind to the actual situation. Hence this criterion should be used in conjunction with other conditions for load shedding.

3) Direction of power flow: This parameter can reflect reliably the sudden reversal of power flow for grid tie. When the plant grid is running with one grid tie, this reversal in power flow is normally caused by short-circuit current, which indicates a potential disconnection of grid tie. When the plant grid is running with two grid ties, sudden reversal of the power flow direction from import to export indicates either some loads have been tripped within plant grid or plant power generator is taking on load from an external grid, all of which predicts operational risks of the plant grid. Hence this criterion should be used in conjunction with other conditions for load shedding.

4) $\Delta P/\Delta t$ where $\Delta P$ is the change in power and $\Delta t$ is a small time period. The signal indicates sudden increase of the power export to utility grid or sudden decrease of the power import from utility grid. However, choosing the value of $\Delta P$ and $\Delta t$ must balance system sensitivity, system response time and minimum necessary loads to shed.

5) Frequency threshold value: The signal can reliably reflect the frequency of plant grid at disconnection. The threshold value should be set higher than the under-frequency load shedding triggering value.

C. Selection of Sheddable Loads

The plant grid consists of four voltage levels: 220kV transmission grid, 35kV main distribution grid, 10kV secondary distribution grid and the urban grid. The main and secondary distribution grids support production loads, and the urban grid provides load for appliance loads, non-production loads and some non-main-production plant loads. Similar to many petrochemical plants, equipments generally come with A and B pumps for redundancy. The typical single-line diagram from power sources to main power equipments is shown in Figure 2.

Fig. 2 Single Line Diagram from power source to main equipment

The selection for sheddable loads shall follow the principles as follows:

1) All of the equipments and facilities in the area supplied by the load from the 35kV main distribution station are allowed to be shut down from the outgoing circuit breaker of 220kV switchboards.

2) The equipments which could stop safely without need of power are allowed to be shut down from the outgoing circuit breaker of 35kV main distribution switchboards or 10kV secondary distribution switchboards.

3) The equipments which stop with need of power shall be treated with care. Most 6kV motors could be shut down with one loop of output lines for power consumption by safe shutdown;

4) Primary pump A and backup pump B for same load shall be shed at the same time;

5) Shed adjacent bus bars that are equipped with bus automatic transfer device.

D. Coordination with Protection Scheme

The load shedding shall be coordinated with protection scheme of the protection relays, upon any occurrence of electrical fault. This is to avoid load shedding command to be issued earlier than protection relay’s tripping action, when the grid is under transient status. Therefore the stability control system will behave in an accurate manner and shed minimum and necessary loads only. Figure 3 is a chronological representation of this coordination.
E. Control Algorithm

Based on the selection of load shedding criteria, the selection of sheddable loads and the coordination with protection scheme, the control algorithm is developed and summarized in figure 4.

Fig. 4 Control algorithm of stability control system

F. Second load shedding

Theoretically, stability control can tackle power gap with precise load shedding, but in reality the power gap is likely to persist. For this reason the stability control system shall examine the frequency constantly, and trigger the second round of load shedding within three seconds if the frequency drops below 48 Hz, which is equivalent to second level of under-frequency load shedding [2],

\[
f_u = f_N \left[ 1 - \frac{1}{K_L} \times \frac{P_{La}}{P_{L, \Sigma N}} \right]
\]

where

- \( f_u \): Frequency resulted from power gap;
- \( f_N \): Nominal frequency value;
- \( K_L \): Load frequency regulation coefficient;
- \( P_{La} \): Active power gap;
- \( P_{L, \Sigma N} \): Total active power load at nominal frequency

Rearranging Equation 1, we can then calculate the frequency after partial load shedding by stability control.

\[
f_u = f_N \left[ 1 - \frac{1}{K_L} \times \frac{P_{La} - P_{Cut}}{P_{L, \Sigma N} - P_{Cut}} \right]
\]

where

- \( P_{Cut} \): Load to shed to achieve targeted frequency

G. Operating Modes

There are five main operating modes in the main grid: Three modes using incoming power line and two modes using island operation. The stability control system should be able to automatically identify different operating modes, and the associated load shedding schemes.

IV. STABILITY CONTROL SYSTEM IMPLEMENTATION

The plant’s stability control system has one master station, three slave stations and 17 child stations, all of which are interconnected by optical fibers. The stations are all based on protection relay platforms installed in parallel with the regular protection and control system.

The master station is responsible for collecting data from the three slave stations and 17 child stations, processing the data and computing the primary and secondary load shedding algorithms. The results are sent to the three slave stations. The master station has redundancy features and an internal “watch dog” which self-reboots the station if a crash would take place. Since the stations are based on a protection relay platform, regular functionalities such as electrical monitoring, display terminals, GPS satellite communication etc is available.

The three slave stations are installed at three power supply points. The slave stations receives signal from the master stations and further dispatches the signals to the child stations.

The 17 child stations each comprises of one or more relays. Each load shedding relay can receive and execute load shedding commands for eight loads. Other relays in the child stations detect and upload electrical parameters upwards in the system hierarchy. The communication
network is 100M Ethernet optic fiber loop, and adopts MIRRORED BITS protocol.

The system has been in installed since early 2008. After initial problems, mostly with the communication network, the system was fully operational in 2009, and has run stable since. The key to the system availability is the quality of the station power supplies, reliability of the stations relay equipments and a stable 100M dual ring Ethernet network.

V. SYSTEM LIMITATIONS AND SUGGESTIONS ON IMPROVEMENTS

The proposed stability control system provides a reliable system for handling the disconnection from grid by the usage of load shedding. However, the system faces some limitations as described below

1. Limited sets of operating modes: The system is configured and programmed based on five different operating modes. This means the system only is predictable and usable under these conditions, and for usage of other operating modes, the system stations need to be re-configured. This leads to an inflexible system and costly modifications.

2. Limited possibility to change load shedding priorities: Since the control system is based on a pre-determined set of loads and load priorities under the operating modes, a change of the priorities of the loads means reconfiguration of some or all of the stations, which is a costly and time-consuming procedure.

3. Limited speed of the load shedding. Given the complexity of the stability control system algorithms, the hierarchy of the stations, and the interaction with the protection scheme, this limits the speed at which load shedding can be done. Currently the speed is sufficient to secure safe plant operation, but if more stringent requirements were needed, it may not be solved with the current system.

4. Limited extension possibilities. Due to the limited number of signals per child station and the limited sets of operating modes possible, additional loads or additional substations means the system needs to be re-designed and re-configured in fully. This introduces limitations on expandability.

A suggested alternative solution to solve the stability control and to improve the above limitations is the usage of a power management system, which is an integrated set of control, supervision and management functions for power generation, distribution and supply for an industrial plant. The main functionalities of a power management system are described below [3].

- Fast load shedding. The primary load shedding of a power management system is fast load shedding, which is based on electrical energy balance calculations. As soon as one or more electrical islands are detected the system calculates if there is enough electrical power available in every individual island to power the loads. If not, the non-essential loads are shed. The shedding process is dictated by priority tables, which are based on the operational conditions of the process. The power management system reacts on changed status of the circuit breakers as the criteria and is fast because it doesn’t wait for a decrease in frequency before it starts to shed loads. Instead, its decision to shed – as well as how much should be shed – depends on the balance between the amount of power generated and consumed in every island. Usually load shedding takes about 100-200 ms, depending of the complexity of the system. Deciding how much power should be shed depends on the number of priorities used and the size of the load shed groups. The load shedding set-up is flexible because an operator can make online adaption of the priority of the various plant loads to the process operating conditions and the electrical network.

- Network determination. By checking the positions of critical circuit breakers in the electrical network and using its internal “knowledge” of the electrical network topology, the power management system uses sophisticated matrix calculations to determine the current operating mode at all given times of the system. Network contingencies must be calculated in a matter of milliseconds after a circuit breaker position has changed. This information can then be used by the load shedding function to calculate imbalances between available and required power.

- SCADA functionalities and integration with protection relays. Since the power management systems is integrated with all protection relays and auxiliary equipment it also includes electrical SCADA functionality such as
  - Generator control including integration with the governor and excitation controller.
  - Circuit breaker control and monitoring
  - Transformer and tap changer control
  - Motor control including integration with motor control centers

- Standard software and hardware: To ensure speed, the load shedding and network determination calculations are done in a high performance controller based on optimized software libraries. To ensure easy expandability, the power management system is based on an integrated set of controller and I/O hardware as well as HMI (Human Machine Interface) software

Based on these functionalities, the main improvements identified by using a power management system for the plant are the following:

- Faster load shedding. The potential to improve the load shedding speed from today's 500 ms down to around 100 ms.
- Improved number of operating modes. Greater flexibility in the plant operations by using the network determination functionality to identify
the current operating mode at all times, and with no reconfiguration costs.

- Instant changes in priority settings directly by operator or maintenance personnel without reconfiguration.

- Flexibility in expansion since the power management system is built on standard and integrated control and HMI software and hardware, made to be easily extended similar to a DCS or SCADA.

- Fewer systems. Since the power management system both encompasses the SCADA and the stability control system, only one system would need to be installed, operated and maintained, interfacing generators, protection relays and other electrical equipment. This would simplify the operations of the plant and further simplify re-configuration and expansions.

VI. CONCLUSIONS

When there is unreliability in the utility grid, and a power disruption may lead to a breakdown of the industrial power grid which can induce a safety risk or production losses, a stability control system needs to be set up.

Analysis shows the target that the plant stability control must defend against is frequency breakdown, and the tactic is load shedding. Important parameters when designing the stability control system is activation criteria, the degree of shedding, which leads to shed and how to determine the selected operating modes. Furthermore, it must be understood how the shedded equipment affects the stability of the remaining power grid.

The stability control system needs to be based on high quality in its critical components, including computing devices, based on relays or controllers, power supplies and the Ethernet backbone. The stability control system must be flexible for reconfiguration and extensions. Therefore dedicated power management system is a possible future improvement.

The real difficulties in setting up stability control involve the selection of criteria and the establishment of control strategy. In the field of stability control for utility power grid, China is a world leader, but the strategy may not be easily transplanted to the industrial grid. The stability control of the plant grid in this study is one of the first industrial stability control systems in China. Although relevant departments have made great efforts on criteria and strategies, and the stability control has passed factory inspection and field debugging, this stability control system has not yet undergone the challenges of great power gap and system disintegration. The plant stability control system will need to undergo further research and improvements regarding its control strategies.

VII. ACKNOWLEDGEMENTS

For the creation of this paper, we would like to express our appreciation to the following people:

Tang Chun Hua, Sheng Zhong Hua and Ju Wei Zhang from SINOPEC Shanghai Petrochemical Co. Ltd. for joining the control strategy study; Li Zhen Hua, Zhu Wei and Lu Zhi Jun from SINOPEC Shanghai Petrochemical Co. Ltd. for making great effort in project implementation; Huang Bing, Xiao Mao Zhi and Jiao Ban from Hui Lun Co. for contributing a lot in the realization of the control strategy; Tao Yu Hua, Ling Xiao Bo and Yu Xu Feng from Shanghai Grid for providing support in the project implementation and approval; Qin Wen Jie from SINOPEC Shanghai Petrochemical Co. Ltd. for playing a key role and taking great responsibility in design approval and final acceptance; Wang Cai Yong from SINOPEC Shanghai Petrochemical Co. Ltd. and Zhou Xiao Guang from ABB (China) Ltd for irreplaceable work in facilitating the publication for this paper. Best regards to above people and others who contributed to the finalization if this paper.

VI. REFERENCES

[1] The petrochemical plant belongs to Shanghai Petrochemical Co. Ltd., a subsidiary of China Petroleum & Chemical Corporation (SINOPEC). The plant is located in Jinshan District of Shanghai and is one of the largest integrated petrochemical complexes in China. By the end of 2010, the plant has possessed a primary crude oil processing capacity of 14,000,000 T/Y producing ethylene, organic chemicals, synthetic resins, synthetic fiber feedstock and synthetic fiber polymers. The plant also has its own power generation capacity and in 2010 produced a total of 2,961,000,000 kwh electricity. http://www.spc.com.cn


VIII. VITA

Zhu Lin Song graduated from Shanghai Tongji University with a major in Electronic Technology, and has a Bachelor degree in Computer Science and Technology from Shanghai Second Polytechnic University. Since 1982, he has been working in SINOPEC Shanghai Petrochemical Co. Ltd. He started as operator, and has since then had various roles as team leader, deputy chief of engineering department and electrical supervisor. At present, his position is deputy chief of equipment department. He is member of electrical specialist network of SINOPEC.

Johan Hansson is a Swedish citizen, graduated from Uppsala University with a M.Sc. degree in Engineering Physics as well as a M.Sc. degree in Business & Economics. He joined ABB group in 2006, serving in various roles within Product Management and Business Development within ABB control system business. Since 2011 he is stationed in Shanghai at ABB (China) Limited as Sales Manager of Electrical Control Systems in China.

Wang Bin holds a B.Eng. in Electrical Engineering from Xi’an Jiaotong University, and M.Sc. in Engineering Management from National University of Singapore. He is Senior Sales Engineer of the Electrical Control System Regional Centre with ABB Pte. Ltd. based in Singapore. Since 2006 he has been actively working to deliver and promote ABB’s electrical control solutions in Southeast Asia, Middle East and China.

Chen Zhang Sheng has Bachelor degree in Computer Science and Engineering from Xi’an Jiaotong University
as well as an IMBA of UBC. In 1990 he joined Shanghai Relay Co. Ltd., first responsible for technology development and new product sales, and later general manager and responsible for technology and marketing. From 2008 to present, he is board chairman and general manager of Shanghai Fang Neng Power Equipment Co. Ltd.

Wu Ming Qing, graduated from Shanghai Tongji University with a major in electric power system and automation in 1982. He has been working in SINOPEC Shanghai Petrochemical Company from graduation to retirement. He used to be planning specialist of planning department of head office, deputy manager and chief engineer of utility department as well as deputy manager and chief engineer of equipment department. He is member of electrical specialist network of SINOPEC.