Abstract

One of the biggest challenges today to modern power grids is maintaining the continuity of power supply to customers, in cases where a main, and vital, component of the grid experiences a fault. This may be proposed to be secured by many ways which will certainly have further cost and environmental impacts. Advanced control systems can be utilized to help automate adaptive actions that will maintain the capacity of grids, with less further investments in the bulky components. This is all possible today due to the advancements in the Intelligent Electronic Devices, IEDs and the availability of a reliable communication system as the back bone. This paper presents the FCCS, Firm Capacity Control System, which is a novel system proposed in order to firmly maintain the capacity of extra-high voltage substations by always making sure the full number of power transformers connecting the 380kV level to the 110kV level which further feeds the 110kV grid and also down to the 13.8kV level. This is crucial to some vital substations in highly populated areas and cities where the peak load is very demanding, and power supply interruption cannot be afforded under any circumstances, even if due to a fault tripping. In case one of the three 380/110kV power transformers is tripped due to a fault, the system will assess the situation based on the available inputs and will take several steps and actions in order to secure and connect the fourth, always-live, standby, power transformer. This system is different from any other, since the switching is done on the high voltage level 110kV which is the downstream. There are a lot of constraints and conditions that this system will have to look at before issuing decisions. These include the pre-fault configurations of both the 380kV and 110kV topologies, the different protection systems in operation, the tap positions of the transformers, etc.

The paper will describe the idea behind this new system, its design, engineering and testing stages, its implementation and its benefits. All the operation steps and actions will be explained including the logic and possible cases and modes that this system operates through. In this paper the authors will also emphasize on how the system is implemented using both centralized and distributed bases, i.e. in one master unit or in more than one Intelligent Electronic Device, IED. The system will be described in both the classical way of implementation and the utilizing of the IEC 61850 communications implementation. Light will also be shed on some of the future suggestions and development of this system.

1. Introduction

In the vastly growing power system transmission grid of Kingdom of Saudi Arabia, a requirement has been put by the operators in National Grid SA to design and implement a new novel control system which ensures the firm capacity of the 380kV Bulk Supply Point (BSP) transmission substation. The definition of firm capacity is the amount of energy (or power) available for production or transmission which can be and must be guaranteed to be available at a given time. The challenge here is to design and implement a smart system that detects disconnection of autotransformer due to internal fault and acts accordingly in very short time to put the standby transformer into service, covering for the failed transformer and avoiding further interruption of valuable power supply. This also overcomes the limitation of not being able having the additional transformer in service all the time, due to higher short circuit rating requirements (Figure 1). Many control systems exist that carry out similar functions like automatic bus transfer, transformer parallel operation, etc. but this is the first control system of its kind, in the authors’ knowledge, to automatically manoeuvre and control the operation of the 502MVA 380/110/13.8kV, bulky, autotransformers.
Figure 1: Increasing the number of transformers in parallel increases the amount of through fault currents, thus increasing required short circuit rating.

In a typical 380kV BSP substation of that kind, (Figure 2) there are usually three voltage levels: 380kV, 110kV and 13.8kV. The 380kV system is one-and-a-half circuit breaker configuration. The 110kV system is a double-busbar single circuit breaker system and the 13.8kV system is a single busbar system.

A Firm Capacity Control System, shortly called “FCCS”, monitors the loss of the power transformers in service and ensures that the supply of demand is maintained without overstressing the system by connecting a stand-by transformer. This is achieved by dynamically monitoring the station topology according to a set of pre-defined rules, defining what to monitor and, in the event of certain triggers, what to be switched. This is achieved via a single IED (ABB REC670) which houses all the logics. The first prototype of the system relies on all field signals being hardwired into the IED, however current developments into future work are now considering all the field signals transmitted over the IEC 61850 GOOSE messaging, utilizing the substation automation technology.

2. Designing the Logic modules of FCCS

The addition of the fourth 380/110/13.8kV 502MVA standby power autotransformer introduced many challenges into the system. The switching on of the stand by transformer in case of tripping of any of the other transformers in service shall be allowed only if the tripping can be identified as a result of an
internal fault in the tripped transformer. FCCS logic shall prevent the switching on of the stand by transformer to a persisting short circuit at any of the outgoing feeders or to a bus bar fault. Internal faults in the tripped transformer are distinguished by observing the performance of the protection system of this power transformer. Tripping of any unit protection like differential protection, restricted earth fault protection, or any transformer mechanical protection shall initiate the FCCS operation sequence. The operation shall be blocked in case of transformer tripping by any other protection e.g. back up over current, back up earth fault, bus and breaker failure protection, etc. which are suspected and usually operating due to a downstream fault on the 110kV level. FCCS is made up of different logic modules. The first module in the start-up logic modules, which decides the readiness of the scheme by monitoring position for all HV apparatus i.e. circuit breakers and disconnecting switches. The position indications are then used to indicate the station (Figure 3) topology needed to evaluate if a valid possible switching condition exist. After any change in the station’s topology, e.g. close or open of a disconnecting switch or circuit breaker, the logic dynamically evaluates the new state to find out if a valid operation situation exists, and if switching of a stand by transformer could be performed.

![Figure 3: Simplified Single Line Diagram the 380/110/13.8kV BSP substation topology.](image)

If the first logic module identifies a valid possible switching condition, the system will go to the ‘ready’ state, else it enters the ‘not ready’ state until a new analysis is triggered (Figure 4). Only in the ‘ready’ state switching operation can be performed (Figure 5).

In every logic cycle, the first logic module checks:

- All input signals and forms the topology-based rules.
- On-Load Tap Changers (OLTC) systems.
- All involved circuit breakers are healthy.
Checking input signals
- Check status of transformers circuit breakers and isolating switches.
- Check position of bus coupler and bus section.
- Check OLTC and all involved CBs are healthy.

All conditions ok?

Logic for stand-by transformer
- Check which transformer is already in service.
- Identify stand-by transformer.

Valid operation conditions?

Set FCCS “not ready”

Set FCCS “ready”

End

Figure 4: Simplified start-up logic of FCCS.

A power transformer is considered in service if:
- Both the status of disconnecting switches and circuit breakers at both windings levels (HV / LV) are closed, indicating that the transformer is connected to (both 380 KV & 110 KV) the busbars.
- Voltage measured at both sides of the power transformer will also ensure that the transformer is in service.
Logic of this module is shown in (Figure 6). There is a similar logic module for each power transformer.

Figure 6: Simplified logic of 'T801 in Service'. The same is applied for T802, T803 and T804.

FCCS finds out which power transformer is the stand-by by checking if:

- Control authority allows FCCS to issue command to control LV CB.
- Status of disconnecting switches and CB at HV side indicates that the transformer is connected to the bus bar.
- Voltage measured at LV side of transformer.

Logic of this module is shown in (Figure 7). There is a similar logic module for each power transformer.

Figure 7: Simplified logic of 'T801 in Stand-by'. The same is applied for T802, T803 and T804.

FCCS finds out whether a transformer is not ready, by checking the following:

- Status of disconnecting switches and CB at HV side is open, indicating that the transformer is not connected to the bus bars.
- Control authority does not allow FCCS to issue command to control LV CB
- When in service transformer is tripped by protection.

Any of the transformers, running in service, gets tripped by the protection system will be flagged by FCCS logic as not ready till the operator resets the tripping relays and the transformer is connected manually (remotely / locally) back to the power system. The process of restoring the power transforms back into service following protection trip will be handled as switching operation to be carried out manually (remotely / locally) by the network operator. We have to make it clear that FCCS logic does not propose to include any provision to automatically restore any transformer after it was tripped by the protection system.
In order to minimize the number of switching operations needed to put the stand-by transformer into service, the following pre-conditions are proposed and assumed during the design process:

- The stand by transformer will always be pre-energized from HV side.
- Isolating switch for 110kV side of the stand by transformer will be closed to one of the 110kV bus bars and 110kV bus sections/couplers will be closed.

When conditions are fulfilled to set the stand bay transformer in service, two verifications processes will start to run:

- The close command will be verified by synchronizing function in order to assure that the stand by transformer CB is not going to be stressed during its closing operation.
- FCCS will take over the duty to equalize the tap position of the stand by transformer with the tap position of the in service transformer. During this process any other control facility for stand by transformer tap changed will be temporary disabled.

The stand-by transformer closing sequence logic module is shown below (Figure 8). The initiation logic modules of closing operation are shown in (Figure 9, 10 & 11) as an example for the first transformer, T801.

![Flowchart of stand-by transformer closing sequence](image-url)

Figure 8: Simplified logic of stand-by transformer closing sequence.
Figure 9: Simplified logic of stand-by transformer closing sequence initiation module.

Figure 10: Second logic module of stand-by transformer closing sequence initiation.

Figure 11: Blocking logic module of stand-by transformer closing sequence initiation.
It has to be also clarified that the transformer On Load Tap Changing Control is set, in our case, to homing mode. Homing mode is applied when a utility may want to retain a spare "hot" transformer that can be immediately connected to the busbar and included in the parallel control function because OLTC position is always synchronised with the parallel transformers in service. Homing facility can be applied to one or more transformers with LV circuit breaker open, which are nominated as part of the parallel transformer group. Tap position on the disconnected transformer is maintained so that its open circuit secondary terminal voltage follows the average set point voltage of the connected parallel group. FCCS is also designed to include modules for tap changers control to handle the tap position of the stand by transformer after being connected to the bus bar following tripping of any transformer in service. The logic is working in accordance with the following principles:

- Topology based logic is used to check if there is valid parallel operation conditions for power transformer.
- The control will be active only during the execution of closing sequence of stand by transformer or when the transformer is in stand-by.

As already explained the design and engineering process of the FCCS logic is achieved to part the logic over different modules. This allows the system to be modular and could be implemented in one or more IEDs that will house all the logic modules or each of the modules, separately. This gives the designer more than one option for implementation. The designer can then choose the option that fits the application the most, increasing reliability by using more than one IED, however, in this case, doubling the cost of implementation. A lot of considerations will drive the implementation.

3. Implementation and Application

We proposed to implement all the logic in one Intelligent Electronic Device (IED) which is ABB REC670. The hardware intended to be used for FCCS shall be 4 instances of synchrocheck, and synchronizing (one per each transformer), 4 instances of automatic voltage control for tap changer parallel control (one per each transformer), 4 instances of tap changer control and supervision with BCD coded input (one per each transformer) in addition to the other basic functions. Input /output modules will be sufficient to accommodate the required process interface signals, e.g. FCCS On/Off, Status signals, etc. The following user interface facility shall be provided

- Local interface at FCCS panel: FCCS ON/OFF selector switch: Used to activate /deactivate the entire system. Test ON/OFF: Used to set the system at test mode by disabling the output to the process. Local /Remote: Used to activate test mode when in local.
- SAS interface at station and network control level: FCCS ON/OFF command: Used to activate /deactivate the entire system. The command will be active only if the local /remote switch at FCCS panel is set to Remote position.

The logic is foreseen to complete all its steps in less than 200 msec, excluding the time necessary for the tap changing equalizing. Any output contact on this REC670 operates in less than 1 msec [1]. This means that if we assume the tap changing takes around 10 seconds in total, there will be a total time of not more than 11 seconds of supply interruption due to the loss of one power transformer. The logic is tailored in the IED using the Application Configuration tool [2]. We are showing an example of the how the logic is implemented below (Figure 12, 13 & 14). Here are examples, of the synchronizing, tap changing and close command logic blocks.

Figure 12: Example of logic implementation using the IED Application configuration tool: Synchronizing logic blocks.
4. Testing the FCCS

As a prototype system, the first edition of FCCS went under extensive testing. The testing was divided into two stages:

1) Logic testing and troubleshooting.

The logic was downloaded to the IED and it was tested on bench. All inputs were actuated and were proving that the logic acts as designed to achieve its function, while recording times. Different scenarios are tabulated to indicate which inputs should be active and which should not, to emulate the actual operating real time scenario. Test sets were used to inject secondary voltages to provide simulation of analogue voltage measurements. This helped verify the logic design and pin-pointed human errors which were corrected in the logic.
II) Overall integrated system testing.

All operating scenarios were tested again, but this time, using the IED in panel and while simulating the analogue and digital inputs. The system is proven in overall manner, meaning that IED is tested along with its connection with FCCS accessories and the external world.

5. Results and Conclusion

All the tests proved the FCCS to be successful on bench and in panel surroundings, as designed and engineered. The times recorded were promising indicating operating times much below 150 msec in total, excluding the tap changing and circuit breaker closing times. For sake of argument it is assumed that the FCCS logic will add 200 msec to the total operation time, in order to be able to estimate the time expected for the transformer outage replacement. This means that the system successfully fulfils the utility requirement of minimizing the time the other transformers are overloaded for. Currently, the system will be commissioned and the plan is to put it into service very soon.

6. Future improvements and suggestions

It is suggested that improvements can be guided in two directions. The first would be having all signals on IEC61850 GOOSE. This means, for example, that transformer protection signals would be multicast from the Protection IEDs, the status signals would be sent from the bay control units and the tap changing signals could be exchanged with the remote tap changing control IEDs. This improvement would save all the hardwiring cables which will mean more cost saving. The second improvement would be distributing the logic over more than one IED. For example, we can have each transformer modules in different IEDs. This will increase the reliability of the system by making the system more redundant. There is also a possibility of having this logic added to the tap changing control IEDs which are of the same type. This will also help reduce the cost of dedicated IED(s). Different future implementations are shown below (Figure 15 & 16).

Figure 15: Future Improvements: Distributing the logic modules over more than one IED to achieve redundancy and increase reliability of system.
Figure 16: Future Improvements: Utilizing IEC61850 Substation Automation GOOSE messaging to exchange status and commands between the FCCS IED and the rest of substation IEDs instead of hardwiring all signals, to reduce cost.

7. References

[1] Bay Control REC670 2.0 Product guide, ABB, 1MRK 511 313-BEN A.