# PLANT-WIDE AUTOSYNCHRONIZATION, BASED ON IEC 61850 AND PROTECTION RELAYS


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***Abstract*** – Synchronizing a single generator to a bus is a pretty straightforward task, for which numerous dedicated devices are available. Managing synchronization of two independently running network parts by a non-generator breaker (for example a tie-breaker) adds more complexity. The complete system is typically built using a synchronizer and selector switches supported by auxiliary relay based logic circuits or a programmable logical controller (PLC).

This paper presents an innovative approach to an industrial plant-wide autosynchronizer solution as a value-added option to the basic functions of the protection relay. The proposed solution covers both the generator breaker(s) and non-generator breaker(s) synchronizing. The solution is capable of recognizing the primary network switch positions and selecting the appropriate participating generating units for feasible operation scenarios. The proposed solution uses International Electrotechnical Commission (IEC) 61850-8-1 Generic Object Oriented Substation Event (GOOSE) signaling between protection relays. The solution does not require any external circuitry to complete the autosynchronizing system.

The features of modern protection relays and IEC 61850 standard enabling the proposed autosynchronizing solution are presented. Comparison of proposed and conventional approaches is made to identify differences and benefits of the former.


*Index Terms* — Autosynchronizer, Protection relays, IEC 61850, GOOSE, Redundant communication, Generator protection.

## I. INTRODUCTION

Successful synchronization of two alternating power sources can be done by matching their frequency, phase sequence, voltage magnitude, and angle. Once these parameters are within a margin a close command is given to the circuit breaker (CB) connecting the two sources. Following this the connection between the two sources is accomplished after the CB closing time. Hence all the conditions of synchronization need to be met at the instant of CB close operation for successful synchronization.

Out of two sources, at least one among them should have option for varying the voltage magnitude and frequency of the system for synchronization i.e., there should exist one generator, to bring the system parameters to meet the conditions of synchronism. Synchronization can take place at generator breaker or at any desired non-generator breaker. Non-generator breaker synchronization needs to identify any one generator available in either network sides, suitable for participating in the process of synchronization.

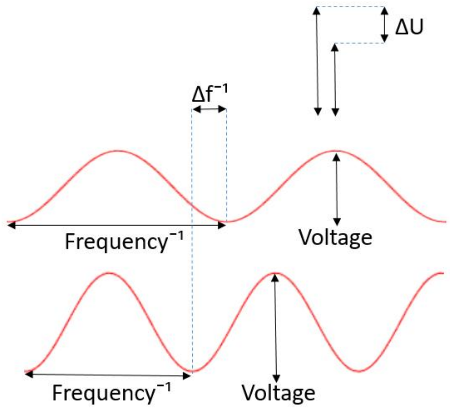


Figure 1: Phase “A” voltage versus time plot of two separately running sources

**Figure 1** shows a situation of phase “A” voltages of two separately running sources. The upper sine wave is from an adjustable source, a generator, and the lower one is from a fixed source. From the two sine waves it can be observed that the adjustable source is running somewhat slower and having lower voltage amplitude than the fixed source. Connecting the two sources together, by closing the CB, under these conditions would lead to a situation where the adjustable source would start importing both reactive and active power from the fixed source. From generator protection point of view the situation would lead to CB tripping due to reverse power and possibly due to under excitation.

The duty of an autosynchronizer is to control the generator output so that the conditions set for the CB closing can be met. As a typical control method the autosynchronizer gives pulse commands to the generator’s excitation system automatic voltage regulator, (AVR) and to the prime mover speed regulator governor (GOV). These commands drive the respective regulators’ set points to either raise or lower the voltage and frequency.

IEC 61850 standard defines the way communication and information exchange should be implemented within electrical network. GOOSE messages allow multicast messages across local area network (LAN) for fast and reliable information exchange between protection and control devices. [1]

## II. CONVENTIONAL APPROACH

### *A. General*

Typical conventional approach is based on a dedicated autosynchronizer cabinet. The cabinet contains an autosynchronizer, two frequency and voltage meters, a synchroscope, and necessary control and selection switches. The cabinet enables both automatic synchronizing and manual synchronizing of a selected breaker. In automatic mode, the operator initiates the process and the autosynchronizer takes necessary AVR and GOV control actions. Once the synchronism is reached, the autosynchronizer closes the circuit breaker. In manual mode the control actions are carried out by the operator. The operator monitors the situation using the two voltage and frequency meters and the synchroscope. Once synchronism is achieved, the operator closes the circuit breaker. As an additional insurance, the manual operation is monitored by a synchrocheck device. The synchrocheck device prevents the operator to close the circuit breaker at a totally wrong moment in time. The synchrocheck functionality can be performed by an additional device or it can be an embedded functionality in the synchroscope.

### *B. Generator Circuit Breaker Synchronizing*

In case the installation includes more than two generators, the described conventional approach has to be extended to serve all of them. The cabinet can serve only one generator at a time, so a “multiplexer” is used. Henceforth, this “multiplexer” is called as selection logic. The selection logic provides correct voltage measurements and control interfaces for the autosynchronizer cabinet. It can be implemented using auxiliary relays, or alternatively with a programmable logic controller (PLC) as shown in **Figure 2** below.

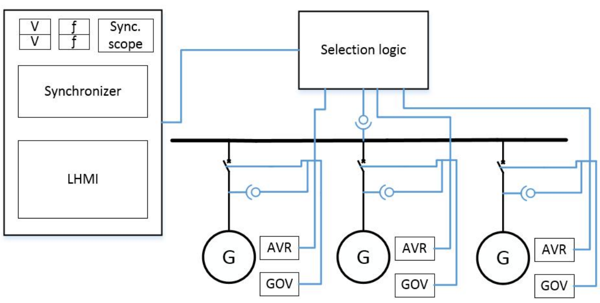


Figure 2: Components in generator CB synchronizing scheme

### *C. Non-Generator Circuit Breaker Synchronizing*

When the installation includes non-generator circuit breakers (**Figure 3**), which are to be synchronized, the selection logic is more complicated. During a non-generator circuit breaker synchronizing, the selection logic has to determine generators participating in synchronization. For complex distributed generation systems with multiple non-generator breakers, the only practical way to implement selection logic is to use a PLC.

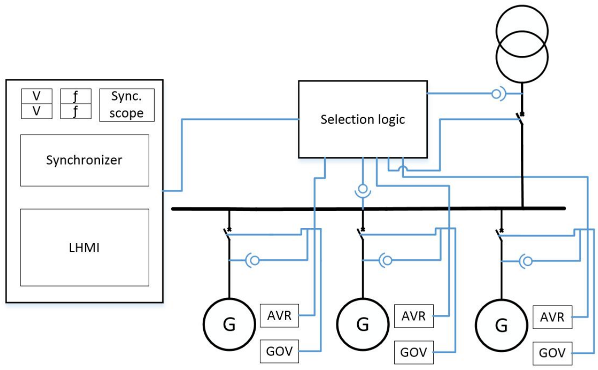


Figure 3: Components in generator and non-generator CB synchronizing scheme

### *D. Real Life Example*

Upstream oil and gas industry used floating, production, storage, and offloading (FPSO) platforms, which often include main generators located in topsides, and essential generators and emergency generators located in hull. Synchronization of these power sources is typically carried out by a dedicated controller in power management system (PMS). **Figure 4** shows selected sections of single line diagram representing a FPSO electrical power system. The synchronization scheme for this FPSO is divided into three groups - Group A which mainly focuses on topside’s circuit breaker, Group B – 690 V switchboard circuit breakers (not shown in **Figure 4**) and Group C comprising of circuit breakers in essential (marine switch room) and emergency board (not shown in **Figure 4**).

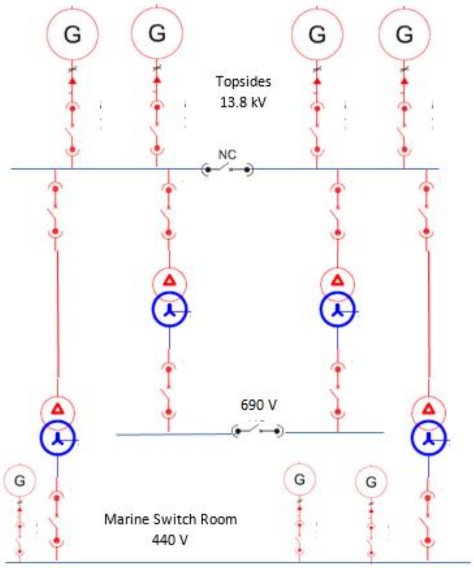


Figure 4: Typical single line diagram for a FPSO

The flowchart in **Figure 5** provides a simple illustration of the process flow from selecting a breaker to starting the synchronization process of non-generator breakers for in the FPSO depicted in **Figure 4**.

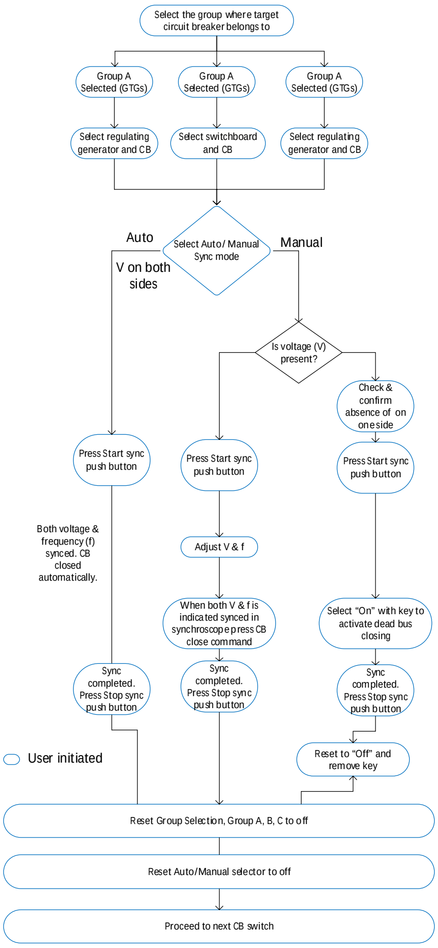


Figure 5: CB synchronisation in a FPSO platform

### *E. User Interface*

In a conventional system, the following user selectable switches are provided on synchronization panel for carrying out safe, secure, and successful auto synchronization. The switches can vary depending on the need to synchronize one generator or two isolated power networks, or for synchronizing generator or non-generator CB.

1. Manual / auto selector switch.
2. Local / remote selector switch.
3. Generator CB selection for synchronization.
4. Non-generator CB selection for synchronization.
5. Generator selection switch for matching the voltage and frequency.
6. Raise and lower push button for voltage and frequency raise lower command.

## III. PROPOSED APPROACH

As mentioned earlier, synchronizing a single generator into a network is a straight forward task. In the proposed approached this would be autonomously carried out by the respective bay protection and control relay (BPCR). In order to explain the advantages of the proposed approach, the following discussion uses a case requiring non-generator breaker synchronization.

Synchronization of two alternating power network parts using non-generator circuit breakers, consists of the following three fundamental steps.

- Identification of probable participating generator(s) for matching voltage and frequency of one of the power network to that of the other.
- Measurement of voltage and frequency difference of the two power networks and sharing this information with selected participating generators.
- Initiate the command to close non-generator circuit breaker to complete the synchronization.

The proposed approach works on distributed control philosophy utilizing features in IEC 61850-compatible BPCRs. The following are pre-requisites for participating BPCRs.

- Auto synchronization feature is part of BPCR.
- Voltage transformer (VT) secondary voltages on both sides of CB (connecting the power networks) are inputs to respective BPCRs.
- Response time of non-generator CBs are known to their respective BPCRs.
- Information exchange between BPCRs is available on IEC 61850-8-1 GOOSE profile.
- Prime mover–generator response characteristics are known to respective generator BPCRs. These characteristics are used for calculating the appropriate pulse duration for raise and lower command for voltage and frequency correction. In the conventional system prime mover–generator response characteristics are available in power management system (PMS).

BPCRs implement the logic using the following four functionalities which depend on the type of bay – generator or non-generator.

1. Non-generator circuit breaker synchronization (NGCBS) functionality.

This functionality is for NGCBS BPCRs and:

- Calculates the voltage and frequency difference of two power networks.
- Checks synchronism conditions.
- Calculates the phase angle difference (advance angle) at which if CB close command is initiated primary contact of breaker will close approximately at zero deg. phase difference.
- Initiates the CB close command, once synchronization condition are met.

2. Generator circuit breaker synchronization (GCBS) functionality.

This functionality is for GCBS BPCRs and:

- Includes all NGCBS functionalities.
- Initiates raise and lower pulses required for voltage and frequency matching.

3. Voltage and frequency matching for non-generator (VFMNG) functionality.
This functionality is for GCBS BPCRs and:
- Initiates the required pulses for voltage and frequency matching.

4. Primary power network topology determination (PNTD) functionality.

This functionality is part of all participating BPCRs. Each BPCR has associated primary equipment (CB and Isolator). GOOSE messaging is used by BPCRs to broadcast their primary equipment connection status, which is used for network topology determination. PNTD functionality:
- Identifies probable participating generator(s) for specific non-generator CB synchronization.
- Provides option to select one or more generator(s) from probable participating generators. In case of multiple generator selection there could be scenario of over correction of voltage and frequency matching hence user can select one generator for fine matching while all remaining selected generator support for coarse matching. Initially all the selected generator participate in voltage and frequency matching up to settable level of matching, once the voltage and frequency difference falls below settable level all the generators except the generator selected for fine tuning is used. The generator selected for fine tuning is henceforth referred as tuning generator.

Table 1 elaborates different steps and information exchange between BPCRs. Notes:
- Unless otherwise mentioned all steps are auto.
- V à Voltage, F à Frequency
- Δ à Difference from reference

| # | Non-Generator CB BPCR | Generator CB BPCR |
|---|---|---|
| 1 | User selects non-generator CB for auto synchronization | - |
| 2 | Identify probable participating generator(s) | - |
| 3 | User identifies generator(s) for coarse V & F matching & fine tuning. | |
| 4 | Measure ΔV & ΔF. | |
| 5 | Broadcast ΔV & ΔF using GOOSE. | Receive ΔV & ΔF from GOOSE. |
| 6 | Check if V & F matching is achieved on non-generator BPCR. | Initiate AVR & GOV correction pulses. |
| 7 | Broadcast V & F match done using GOOSE. | Receive V & F match done from GOOSE. |
| 8 | Initiate the CB close command | |

Table 1: Information exchange between BPCRs

The flowchart in **Figure 6** provides a simple illustration of the process flow from selecting a breaker to starting the synchronization process

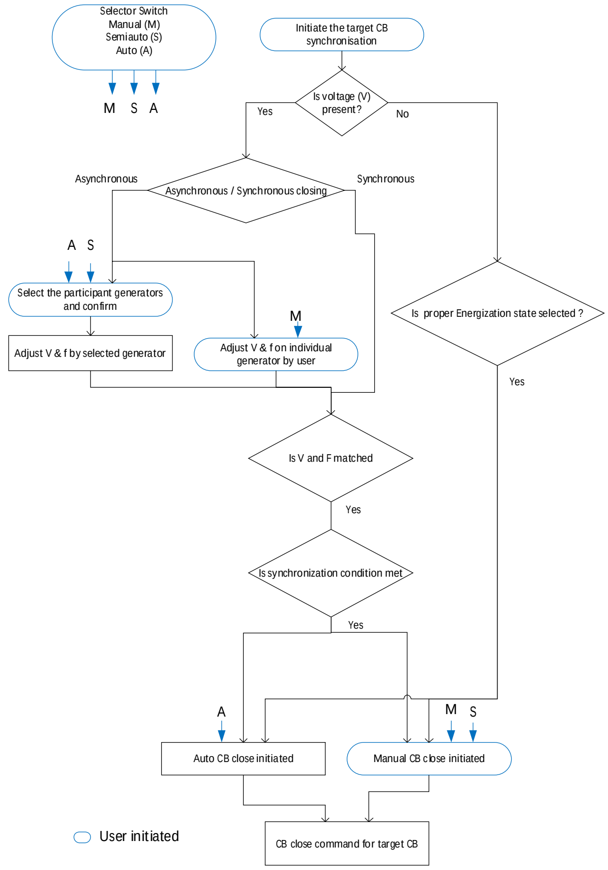


Figure 6: Typical flow chart for CB synchronisation in proposed approach

## IV. EXAMPLE CASE STUDY

### *1. System Description*

Double bus bar with bus coupler configuration is considered for the example shown in **Figure 7**. The system has four generators (GEN1, GEN2, GEN3 and GEN4), two grid utility connection nodes (GRID1 and GRID2) and a bus coupler (BC).

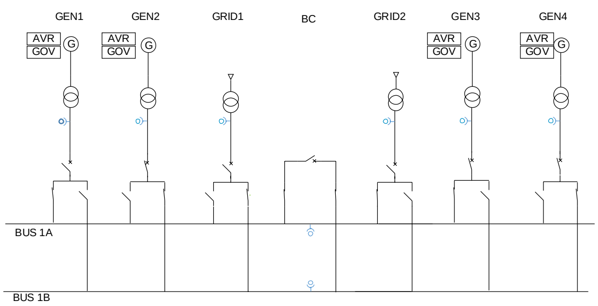


Figure 7: Example system configuration

## 2. *Synchronization Requirement*

The following need to be synchronized in sequence.

i.) GRID1 synchronization
ii.) GEN1 synchronization
iii.) Bus coupler (BC) CB synchronization.

## 3. *Conventional Approach*

Figure 8 depicts equipment / components required and wiring connections in symbolic form to achieve plant-wide auto synchronization by conventional method.

The synchronizer and operator interface with various selection switches and meters are located in the synchronization panel. The panel further includes a selection logic based on auxiliary relays.

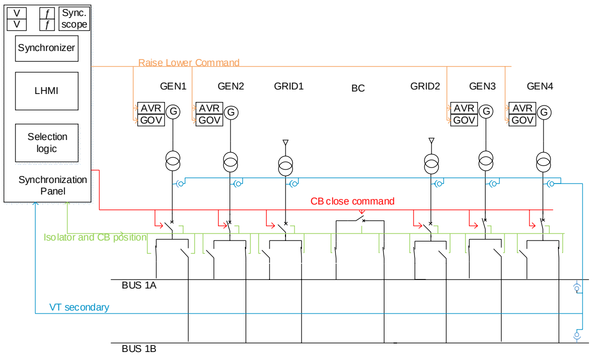


Figure 8: Equipment and connections required for conventional approach.

### GRID1 CB synchronization

The following steps are used:

1. Operator selects:
   a. GRID1 CB for auto synchronization on synchronization panel using the selector switch.
   b. Generator GEN2 (as an example) for matching voltage and frequency.
2. Selection logic extends the VTs' secondary to synchronizer (synchronization panel). In this example the isolator connecting GRID1 and BUS 1B is closed, hence selection logic extends the GRID1 VT and Bus1B VT secondaries to the synchronizer.
3. Synchronizer initiates the raise and lower pulses for matching.
4. Selection logic sends raise and lower matching pulses to GEN2 GOV and AVR.
5. GEN2 GOV and AVR adjust BUS1B voltage and frequency to GRID1 voltage and frequency, respectively.
6. The voltage and frequency is matched.
7. Synchronizer issues CB close command at appropriate phase angle difference (for example +-10 deg.)
8. Selection logic sends close command GRID1 CB.
9. GRID1 CB closes and the synchronizing system returns to the stand-by mode.

### GEN1 CB synchronization

The following steps are used:

1. Operator selects the GEN1 CB for auto synchronization on synchronization panel using the selector switch.
2. Selection logic extends the VTs' secondary to synchronizer. In the example case isolator connecting GEN1 and BUS 1A is close hence selection logic extend the GEN1 VT and Bus1A VT secondaries to synchronizer.
3. Synchronizer initiates the raise and lower pulses for matching.
4. Selection logic sends the raise and lower pulses to respective generator (in the example case GEN1) GOV and AVR.
5. On receiving matching pulses GOV and AVR of GEN1, matches the GEN1 voltage and frequency to that of BUS1A voltage and frequency.
6. The voltage and frequency is matched.
7. Synchronizer issues the CB close command at appropriate phase angle difference.
8. Selection logic sends this command to selected GEN1CB.
9. GEN1 CB closes.

### Bus coupler (BC) CB synchronization

Following steps are used:

1. Operator selects the BC CB for auto synchronization on synchronization panel using the selector switch. Additionally the operator selects the generator (GEN3 as an example) for matching voltage and frequency.
2. Selection logic extends the VTs' secondary to synchronizer. In the example case selection logic extend the BUS1A VT and Bus1B VT secondaries to synchronizer.
3. Synchronizer initiates the raise and lower pulses for matching.
4. Selection logic send the raise and lower pulses (matching pulses) to selected generator (in the example case GEN3) GOV and AVR.
5. On receiving matching pulses, GOV and AVR of GEN3 matches the BUS1A voltage and frequency to that of BUS1B voltage and frequency.
6. The voltage and frequency is matched.
7. Synchronizer issues the CB close command at appropriate phase angle difference.
8. Selection logic send the command to selected CB. In the example case selection logic sends this command BC CB.
9. BC CB closes.

## 4. *Proposed implementation*

As a pre requisite every BPCR have required functionality as mention earlier. Table 2 below summarize the functionality available in each BPCR.

| Bay protection and control relay Name | Functionality list |
|---|---|
| BPCR-GEN1, BPCR-GEN2, BPCR-GEN3, BPCR-GEN4 | GCBS , VFMNG and PNTD |
| BPCR-GRID1, BPCR-GRID2 BPCR-BC | NGCBS and PNTD |

Table2: Functionality available in BPCRs

The table 3 below summaries the necessary connections with respective BPCRs.

| Bay protection and control relay name | Connections (Hard wired) |
|---|---|
| BPCR-GEN1 | · Isolator positions connecting generator to BUS1A and BUS1B.<br>· GEN1 VT secondary measurement<br>· BUS1A and BUS1B VT secondary measurements<br>· GEN1 , CB position<br>· GEN1 CB close command for closing the CB.<br>· Raise /Lower pulse command to GEN1 , GOV for frequency matching as outlined in figure 6<br>· Raise /Lower pulse command to GEN1, AVR for voltage matching as outlined in figure 6 |
| BPCR-GEN2 | · As with BPCR-GEN1 |
| BPCR-GRID1 | · Isolator positions connecting grid incomer 1 to BUS1A and BUS1B.<br>· GRID1 VT secondary measurement<br>· BUS1A and BUS1B VT secondary measurements<br>· GRID1 , CB position<br>· GRID1 CB close command |
| BPCR-BC | · Isolator position connecting BC to BUS1A and BUS1B.<br>· BUS1A and BUS1B VT secondary measurements<br>· BC , CB position<br>· BC, CB close command |
| BPCR-GRID2 | · As with BPCR-GRID1 |
| BPCR-GEN3 | · As with BCPR-GEN1 |
| BPCR-GEN4 | · As with BCPR-GEN1 |

Table 3: Hard wired information for each BPCR

Apart from needed functionality and wired connection all BPCRs are able to exchange information over IEC 61850-8-1, GOOSE profile.

The Figure 9 depicts the needed equipment, components, wiring connections and GOOSE communication between each BPCR in symbolic form. Target is to achieve the plant wide auto synchronization as per the proposed implementation.

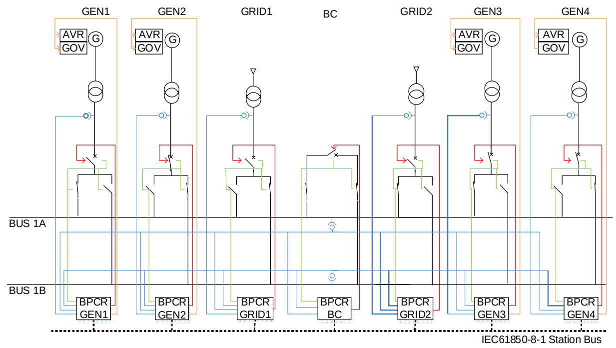


Figure 9 : Equipment and its connection for proposed implementation.

As per Figure 9, following are various equipment connection status

- GEN1-CB is open but isolator connected to bus 1 A (ISO 1A) is closed
- GEN2-CB and ISO1B are closed
- GRID1-CB is open but ISO 1B is closed
- BC-CB is open but ISO 1A and ISO 1B are closed
- GRID2-CB is open but ISO 1A is closed
- GEN3-CB and ISO1A are closed
- GEN4-CB and ISO1B are closed

**GRID1 CB synchronization**

Following steps are used:

1. Operator selects GRID1 CB for auto synchronization on BPCR-GRID1
2. PNTD functionality identify the probable generator list. All the CBs and isolators positions are available from other BPRCs on IEC 61850-GOOSE profile. In the example case GEN2 and GEN4 are probable generators to participate in voltage and frequency in example case.
3. Operator selects the generator(s) out of the available ones. In the example case operator selects both GEN2 and GEN4. Operator also selects the GEN2 as the tuning generator. Intention is to do coarse matching using both of the generators participating. When the coarse adjustment is achieved, GEN2 only will fine tune the voltage and frequency difference.
4. NGCBS functionality of GRID1-BPCR sends the voltage and frequency differences to all generators on IEC 61850-GOOSE profile
5. BPCR of GEN2 and GEN4 receives the voltage and frequency difference on IEC 61850-GOOSE profile. Other generator BPCRs in the system receive the information as well, but they ignore it.

6. PNTD functionality of GEN2 and GEN4 extends the voltage and frequency difference to its own VFMNG functionality. This functionality calculates the required raise/lower pulse commands for matching the voltage and frequency. This is carried out based on each generator's unique properties.
7. Raise/lower pulse commands for voltage and frequency matching is connected to its own AVR and GOV respectively.
8. On receiving matching pulses, GOV and AVR of GEN2 and GEN4, matches the BUS1B voltage and frequency to that of GRID1 voltage and frequency up to coarse level (settable).
9. BPCR-GEN4 disable the raise /lower pulses. BPCR-GEN2 still continue initiate the raise/lower pulses to match up to fine level
10. Once the matching is achieved, BPCR-GRID1 sends the generator deselection information on IEC 61850-GOOSE on GEN2.
11. BPCR of GEN2 stop generating the raise/lower pulses to AVR and GOV.
12. Once the voltage and frequency is matched NGCBS at BCPR-GRID1 initiates the CB close command at appropriate phase angle difference.
13. GRID1 CB closes.

**GEN1 CB synchronization**

Following steps are used:

1. Operator selects GEN1 CB for auto synchronization on BPCR-GEN1.
2. GCBS functionality of BPCR-GEN1 identify the voltage difference as per bus isolator positions. In the example case isolator connecting GEN1 and BUS 1A is closed hence GEN1 VT and Bus1A VT secondaries are selected for matching.
3. GCBS functionality of BPCR-GEN1 initiates raise and lower pulses for matching.
4. Raise/lower pulse commands for voltage and frequency matching are connected to its' own AVR and GOV respectively.
5. On receiving matching pulses, GOV and AVR of GEN1 match the GEN1 voltage and frequency to that of BUS1A voltage and frequency.
6. Once the voltage and frequency is matched (as required), GCBS functionality of BPCR-GEN1 issue the CB close command at appropriate phase angle difference.
7. GEN1 CB closes.

**Bus coupler (BC) CB synchronization**

Following steps are used:

1. Operator selects bus coupler CB for auto synchronization on BPCR-BC.
2. PNDT functionality of BPCR-BC identify the probable generator list. In the example case it identifies two list. List 1 comprises of GEN2 and GEN4 and List 2 has GEN3 as another probable generator.
3. Operator selects the generator(s) from the either of the (step2) lists. In the example case operator selects the GEN3. It is not possible to select participating generators from different lists.
4. NGCBS functionality of BPCR-BC, sends the voltage and frequency differences to all generator BPCRs on IEC 61850-GOOSE profile.
5. BPCR-GEN3 receives the voltage and frequency difference on IEC 61850-GOOSE profile. Other generator BPCRs within the system receive the same information, but they ignore it.
6. PNDT functionality of BPCR-GEN3 identify its selection and extends the voltage and frequency difference to its own VFMNG functionality. This functionality calculates the required raise/lower pulse commands for matching the voltage and frequency.
7. Raise/lower pulse commands for voltage and frequency matching is connected to respective AVR and GOV.

8. On receiving the matching pulses, GOV and AVR of GEN3 matches the BUS1A voltage and frequency to that of BUS1B voltage and frequency.
9. Once the matching is achieved, BPCR-BC, send the generator deselection information on IEC 61850-GOOSE to GEN3.
10. BPCR of GEN3 stops generating the raise/lower pulses to AVR and GOV.
11. Once the voltage and frequency is matched, the NGCBS functionality of BPCR-BC initiates the CB close command at appropriate phase angle difference.
12. BC CB closes.

## *5. Comparison*

Table 4 below summarizes the different aspects of comparison.

| Criteria | Conventional implementation | Proposed implementation |
|---|---|---|
| Specific equipment / component | Synchronizer device, various selector switches, auxiliary relays for the selection logic and a cabinet. | No specific need as functionality is an integral part of BPCR, including operator's LHMI. |
| Additional hard wiring | Yes, as outlined in fig 8. | No additional need as BPCRs already have all the relevant local information and data from other devices are available on IEC 61850-8-1 GOOSE profile. |
| Commissioning time | More | Less |
| Engineering time | Less, in case of a repeat design. Otherwise, More. | Even or more, depends on the system complexity. |

| | | |
|---|---|---|
| Availability | Low or moderate, depending on system design details. | Very high, as the complete functionality available on protection relay. |
| Diagnostics capabilities and fault finding effort | Very limited self-diagnostics. Fault finding can be time consuming. | Comprehensive self-diagnostics. Fault finding relatively easy. |
| Communication network dependency | Typically low. High in case the selection logic is implemented based on distributed PLC units. | High for the complete functionality, but manual emergency operation possible even without communication |
| Probability for human error | Typically low, but depends heavily on the actual detailed design. | Very low |

Table 4: Comparison of solutions

## V. CONCLUSIONS

The paper proposes a new approach for plant-wide autosynchronization solution. The proposed solution is based on use of distributed BPCRs perform synchronization for its associated circuit. The BPCRs shall contain specific functionality to support the synchronizing process, in addition to their normal protection and control functions.

In case of a non-generator breaker BPCR, the local synchronizing related functionality is not enough. Such a BPCR needs additional functionality to recognize generators that can be engaged for the synchronization process with the help of primary network switching equipment status and generator operating mode. Obviously, this distributed intelligence requires fast and reliable information exchange between all the related BPCRs. The IEC 61850-8-1 GOOSE profile offers excellent method for standardized and supervised information exchange between the BPCRs.

The paper also presents a comparison between the conventional and the proposed solution on a conceptual level. The proposed solution eliminates hard-wired synchronizing equipment and requires fewer manual inputs resulting in an increase of overall system reliability. The commercial viability of the proposed solution has not been addressed here, but taking into account the synergies it could have with BCPRs' basic duties, a positive result is expected.

## VI. REFERENCES


[1] IEC 61850-8-1.; Communication networks and systems in substations - Specific Communication Service Mapping (SCSM) Mappings to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3, *International Electrotechnical Commission (IEC)*


## VII. VITA

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