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Development of a Generalized Scaled-Down Realistic Substation Laboratory Model for Smart Grid Research and Education

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ABSTRACT This paper introduces a physical scaled-down realistic substation laboratory model development for translational research and education in smart grids. The development of a substation panel with four 3- ϕ feeders of 415 V, 65 A rating is described in detail. The developed substation model can be configured to realize seven widely used substation bus bar arrangements. A programmable logic controller (PLC) is used to create interlock mechanisms for mimicking the actual substation operation practices. Provision is made to realize the gang and independent pole operation of circuit breakers, the manual and remote modes of operation, and different types of current transformer arrangements. The substation panel can host up to 10 commercial IEDs, and multiple substation panels can be cascaded to form a bigger station using the master-slave configuration of PLCs. All the potential transformer and current transformer measurements, circuit breaker, isolator, and earth switch status signals are made available for connecting field devices. The developed substation model can be used for advanced research on substation automation using IEC61850, validation of new protection strategies, implementation and testing of new algorithms (such as topology processing, state estimation) for energy management systems (EMS) like how they get implemented in the field.

INDEX TERMS Substation, bus bar arrangements, bus-breaker model, interlock logic.

I. INTRODUCTION

The fusion of sensors, edge computing, data sciences, high-performance computing platforms, information and communication technologies (ICT) is driving every traditional engineering domain into a new data-driven operational paradigm. The electric utilities will have no exception for such innovations as they are rapidly adopting the integration of information and communication technologies into their systems [1], [2].

The majority of the sensors in power systems are deployed in substations, acting as data sources. The acquired data is consumed by the energy management system (EMS) applications at control centers. Power engineering researchers hardly find access to substations and control centers for experimentation. This necessitated the development of the scaled-down

physical testbeds and the hardware in loop real-time simulation testbeds across the world [1]–[10]. A smart grid testbed is developed for research on wide-area monitoring, protection, and control (WAMPAC) in Energy Systems Research Laboratory (ESRL) at Florida International University [1], [2]. Power electronic converter based re-configurable power system emulator with measurement and communication infrastructure is developed at University of Tennessee-Knoxville [3]. Analog Power Simulator (APS) is upgraded and automated to deploy a human-immune-based multi-agent system (MAS) in [4]. A large-scale Jeju island (South Korea) smart grid testbed development is discussed in [5]. A smart home energy testbed is presented in [6] with renewables and demand-side management. Various other testbeds are also developed to study the impact of renewable integration in micro-grids [7]–[9]. IEC 61850 enabled substation automation systems testbed at University Grenoble Alpes and Queen’s University Belfast [11], [12], SCADA test-beds

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for analyzing security of SCADA control systems at Idaho, Pacific North West, Sandia and Oakridge National Laboratories, Arizona State university, USA, IIT Kanpur, Jamia Milla Islamia University, India, Royal Melbourne Institute of Technology (RMIT) [13]–[17] are some examples.

Substation automation research presented in [11] and [12] considers substation as a simple node. A simulation model of the 24-bus IEEE Reliability Test System (RTS) is proposed in [18] emphasizing the importance of bus-breaker models over bus-branch models. The testbeds presented in [19] demonstrate the IEC 61850 based substation automation system with a single bus-single breaker configuration. In [20], a radial feeder model is used for the protection laboratory. Prototype of a real 110 kV substation is reproduced at 1/10 scale in [21] using the three dimensional models of operating material and power equipment of substation. Most of the existing laboratory testbeds reported in the literature use bus branch models i.e. they consider substation as a single node as shown in Fig.1(b). The bus branch models are widely used in planning and operational studies [18]. The bus branch models are derived from the substation bus-breaker (node-breaker) configurations, which are actual field implementation arrangements [18], for simplified modeling and analysis. Bus branch models are not suitable for the circuit breaker related studies, detailed protection studies and topology processing applications. The complexity of protection schemes gets significantly affected by the substation configuration used and the available current transformer (CT) arrangements.

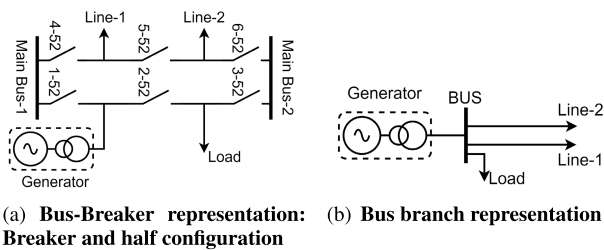


FIGURE 1. Bus-branch and bus-breaker models.

From the author's interactions with several practicing engineers/researchers in India, it is realized that many of them understand the importance of substation configurations, associated CT arrangements in actual protection schemes implementation only through the field experience. Only bus-branch based protection and analysis is known to most of them. In order to bridge this gap between the industry, academic education, and research, an attempt is made to design a scaled-down physical substation model mimicking the real substation in a laboratory as much as possible. Contributions of this paper are as follows,

- Proposed a generalized scaled-down physical substation model which can be configured to realize all the standard bus bar configurations used in 11 kV to 1200 kV voltage levels as per IEEE Std C37.234-2009 [22].

- A single line diagram of the proposed implementation which facilitates realization of various bus bar configurations in a single laboratory substation is provided.
- Implementation details of the developed substation model with four 3- ϕ feeders of 415 V, 65 A rating are provided.
- Selection procedure of power contactors for emulation of circuit breakers and isolators is discussed.
- Typical current transformer (CT) and potential transformer (PT) arrangements and their incorporation into the developed substation are explained.
- The operating procedure used for realization of different bus-bar configurations in the developed substation panels and the associated programming logics used in the PLC are discussed.
- Details of interlock logics implemented in PLC to mimic the field implementation practices followed by Power Grid Corporation of India (PGCIL) for isolators, earth switch and circuit breakers are presented.
- One sample use-case of realizing a 440 kV/110 kV transmission substation bus bar arrangements in the laboratory using the developed generalized substation panels (GSP) is described.

II. BUS-BREAKER CONFIGURATIONS

Bus-Breaker configurations are practical implementation structures used for the connectivity of electrical components in a substation [22]. These configurations dictate the protection philosophies, associated CT/PT configurations, the number of SCADA inputs and outputs, and reliability of the substation.

Many bus-breaker arrangements are being practiced in high voltage substations [23]. The major station arrangements are listed below [22], [24],

- 1) Single bus - single breaker (SBSB)
- 2) Double bus - single breaker (DBSB)
- 3) Main and transfer bus (MTB)
- 4) Breaker-and-a-half (one and half breaker) (BH)
- 5) Double bus-double breaker (DBDB)
- 6) Ring bus (RB)

The majority of the high voltage substations (132kV to 400kV) in India use scheme 4. Most of the substations in power plants use scheme three, or its variant double main transfer bus scheme (DMTB). Scheme 5 is used in 765kV, and above substations [23].

The following sections describe a substation model used in the laboratory which allows the realization of any of the above discussed schemes in a single substation. This model is proposed only for scaled-down physical substation model development for laboratory use. Its suitability and applicability for real substation implementation, modeling and simulation purposes is beyond the scope of the paper. Primary emphasis is on the Bus-Breaker station arrangements, circuit breaker (CB), isolator, earth switch emulation, their interlock mechanisms, current and potential transformer (CT, PT)

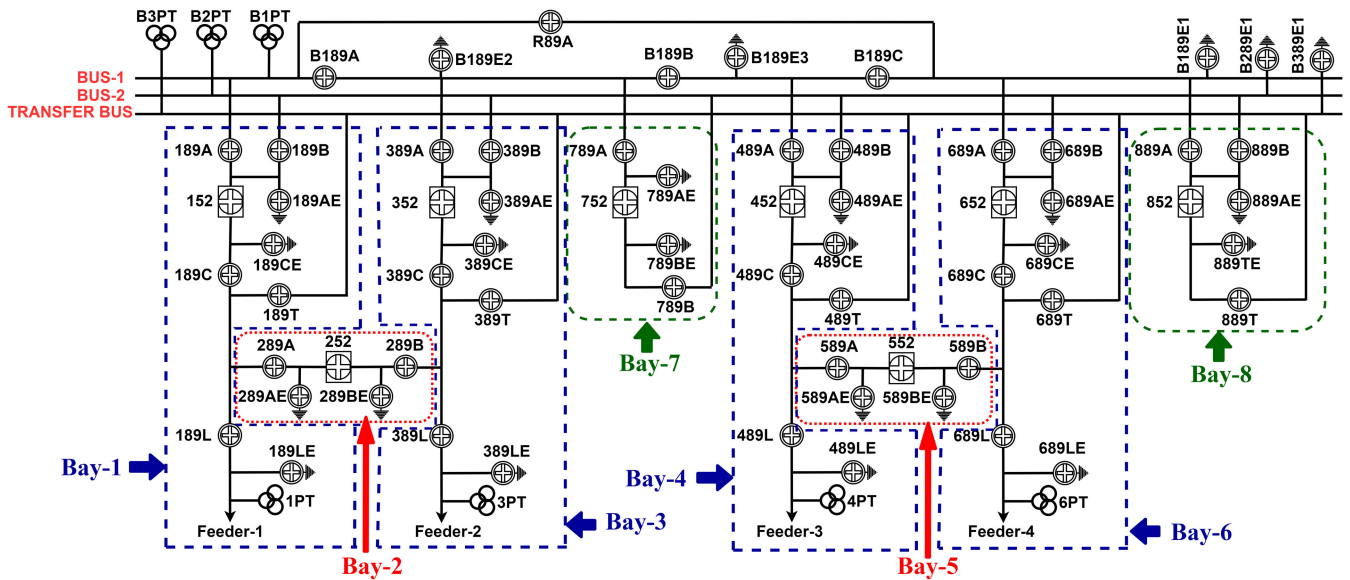


FIGURE 2. Proposed generalized substation laboratory model single line diagram.

arrangements, remote and local operation of the substation, and synchronization.

III. PROPOSED GENERALIZED SUBSTATION MODEL

The single line diagram (SLD) of the proposed generalized substation model for laboratory implementation is shown in Fig.2. The substation model has three buses designated as Bus-1, Bus-2, and Transfer Bus, as shown in Fig.2. There are 8-Bays associated with 8 circuit breakers used in the generalized substation model. It serves four feeders, and the corresponding bays are designated as Bay-1, Bay-3, Bay-4, and Bay-6. Bus coupler-Bay, for electrically connecting Bus-1 and Bus-2, is defined as Bay-7. Transfer bus coupler bay, for electrically connecting Bus-1 or Bus-2 to the transfer bus, is designated as Bay-8. Bay-2 and Bay-5 represent the middle breaker bays for realizing breaker-and-a-half schemes. Standard symbols, 89 for isolator, PT for potential transformer, CT for current transformer, and 52 for circuit breaker (CB), are used in the SLD. 89L represents the line isolator. The number before these symbols indicates the corresponding bay number. The letter E at the end of the isolator number 89 represents the corresponding earth switch.

In the Bays-1,3,4,6,7, and 8, the isolators 89A, 89B & 89T are used to connect the corresponding circuit breakers (CB) to Bus-1, Bus-2, and transfer bus as desired. In Bay-2 & Bay-5, the isolators 89A and 89B connect the corresponding CBs to feeder bays at both ends. This arrangement allows the realization of all the configurations requiring two bus bars (DBSB, MTB, NH, DBDB). It can be observed that Bus-1 is split into four parts using the isolators B189A, B189B, and B189C. The first section and the fourth section of Bus-1 are connected through isolator R89A. This arrangement is proposed to realize the ring bus configuration. The proposed



FIGURE 3. Six substations installed in the SESI-HTB.

SLD enables reconfiguration of a single substation to realize any standard bus bar arrangements, which is a unique contribution of the paper.

A. DEVELOPED SCALED-DOWN SUBSTATION PANELS

Six substations are manufactured to realize the proposed SLD and installed in the laboratory. Fig.3 shows the installed generalized substation panels (GSP) in the laboratory. Each substation model consists of three vertical panels of length-2.4m, breadth-1m, and height-2.4m. It also contains three smaller cubic panels, on the top of the vertical panels, of length-2.4m, breadth-1m, and height-0.5m, as shown in Fig.4. Each vertical panel, including the top cubic panel, is denoted as GSPA, GSPB, and GSPC from left to right in the picture. The picture shown in Fig.4 is an assembled picture from



FIGURE 4. The generalized substation panel.

individual panel pictures taken separately, because a single picture of all the sub-panels together in a vertical position could not be obtained due to space constraints for taking a photo in the laboratory. Two substation models on the left, two on the right, and two at the rare end can be observed in Fig.3.

The components of all the Bays are hosted in GSPA and GSPB as follows:

- The front side of GSPA panel - Bays 1, 2;
- The backside of GSPA panel - Bays 3, 7;
- The front side of GSPB panel - Bays 4, 5;
- The backside of GSPB panel - Bays 6, 8.

The front and back doors give access to the panel components. A middle plane in the GSPA and the GSPB panels hosts all the power components. The GSPC panel middle plane hosts a Schneider make a programmable logic controller (PLC) and CR-M miniature relays for providing interlocks. The top cubic panels host all the line isolators contactors, PTs, and terminal blocks for external connections.

A MIMIC of the SLD, is provided on the front side of the GSPA and the GSPB panels for manual operation of the substation, just like a real substation, see Fig.3. TNC switches are provided to manually operate isolators, CBs, and earth switches from the MIMIC. The TNC switches corresponding to the circuit breakers are also equipped with locks to avoid an accidental opening during the system operation. Semaphore indicators, a Red vertical strip indicating closed position, Green horizontal strip indicating open position, are used in the MIMIC to show the status of CBs, isolators, and earth switches. GSPC panel with mounting plates on the front and the back doors can host up to 5 commercial IEDs on

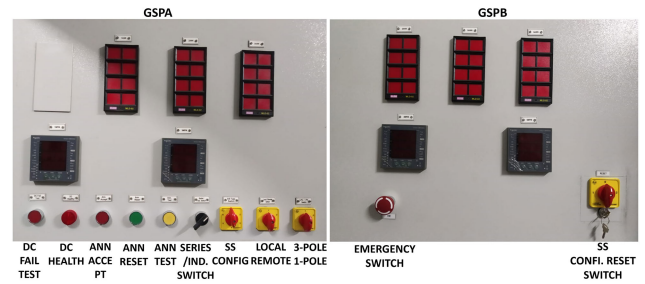


FIGURE 5. Options provided on the GSPA and GSPB panels.

each door. Fig.5 shows the indicators and options provided on GSPA and GSPB. Six annunciators with eight segments and four multi-functional meters are provided. Other options available on the GSPA are as follows:

- Push button switches for DC fail test, annunciator accept, reset and test.
- A red indicator light is provided for indicating DC healthy status.
- One TNC switch (black color) is to select SERIES/INDEPENDENT operation of substation. Using the SERIES option, two or more substations can be cascaded to realize a bigger substation. The master-slave configuration of PLCs is used to achieve this feature.
- Three yellow color switches, The first switch (left to right, label: SS CONFIG) has six options for selecting different bus-bar configurations. The second yellow switch (label: LOCAL/REMOTE) has two options for selecting substation operating modes, local operation (using MIMIC) or remote operation (using SCADA). The third yellow switch (label: 3-POLE/1-POLE) has two options for selecting 3-pole/GANG operation of the CB or single-pole operation of the CB.

On the GSPB panel, an emergency switch is provided to disconnect DC and AC supply to the substation panel. The emergency switch also gets activated when the doors are open during the substation energization. One yellow color reset switch (CONFIG.RESET SWITCH, see Fig.5) is provided on the GSPB to reset all CBs, isolators, and earth switches to default (open) positions. This switch needs to be used by researchers for changing one substation configuration to another configuration. Blue color synchronizing sockets (8 Nos) are provided at the bottom of the GSPA and the GSPB panels for each CB. A synchronizing trolley is developed using commercial synchro check relays of Alstom make. A dedicated 24V DC battery supply is used for the control circuit of the substation model. The panels manufacturing and internal wiring as per the SLD are developed in collaboration with a local vendor. The complete PLC programming to achieve the features is done by the authors. All the six substation arrangements discussed in the previous section can be realized using the proposed design. Double-bus single-breaker with transfer bus configuration is a software configurable option in the PLC.

B. EMULATION OF CIRCUIT BREAKERS, ISOLATORS, AND EARTH SWITCHES

Circuit breakers can be treated as ideal switches for most of the power system operational studies (including protection). However, the operating time of CB varies based on the CB type like SF6, vacuum CBs, etc. In India, substations with operating voltages below 132 kV predominantly use gang-operated SF6 CBs, and substations with an operating voltage of 132 kV and above use single pole operated SF6 CBs. To mimic substation operation of any voltage level, each CB is realized using a 3-phase power contactor for gang operation and three single-phase power contactors for independent pole operation, as shown in Fig.6. The 3-POLE/1-POLE switch on the GSPA can be used to select either of the two modes of CB operation. The maximum operating time of SF6 CBs is around three cycles. The power contactor used for CB operation should operate within the operating times of the SF6 CBs. Opening and closing times of different 3-phase contactors from ABB, SIEMENS, and SCHNEIDER are compared in Table.1.

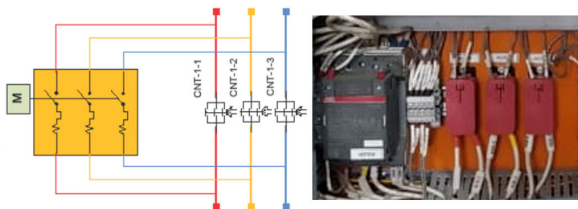


FIGURE 6. Circuit breaker emulation in the panel.

TABLE 1. Opening and closing time of 3-φ contactors.

Type	Opening time	Closing time	Rated current
ABB	37-47 ms	25-55 ms	116 A
Schneider	40-75 ms	20-35 ms	115 A
Siemens	14-20 ms	90-230 ms	95 A

ABB contactor is selected for the emulation of gang-operated CBs as it closely satisfies the operating time requirements. GIGAVAC make 1-φ contactors with an opening time of 8 ms and closing time of 25 ms are used to emulate independent pole operation. Each CB will have two isolators and two earth switches at both ends, which is a standard practice in substations. Isolators are emulated using low-cost 65 A ABB power contactors as they need not open at the same speed as CB. All the power contactors used for CBs, isolators, and earth switches are normally open (NO) type. Color-coded TNC switches, Black for isolators, Red for CBs, and Green for earth switches, are used for manual operation. Lockable TNC switches are used for CBs to prevent unwanted operation while running the substation as a safety measure. Fig.7 shows CB, isolator, and the earth switches in the MIMIC.

C. CURRENT TRANSFORMER AND POTENTIAL TRANSFORMER ARRANGEMENTS

In India, a variety of protection system implementation practices involving various CT arrangements are followed in the high voltage substations [23]. Depending on the protection

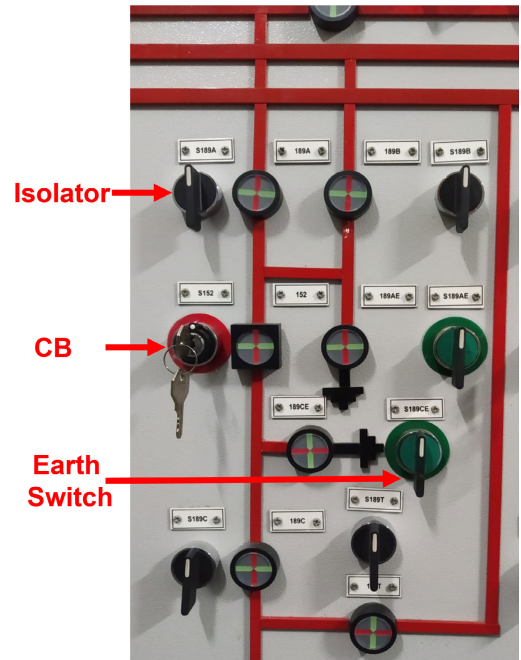


FIGURE 7. Circuit breaker, isolator and earth switch in MIMIC.

requirements, there can be 3 to 8 CTs placed in each bay. Usually, 0.2 class and PS class CTs are used in the field. Each CT normally consists of 3 to 5 secondaries based on the metering, protection, and backup requirements. This makes the wiring in substations very complex, and automation plays a very important role in simplification. However, researchers are never exposed to these practices in academic institutions. This project bridges the gap. Fig.8 shows possible CT arrangements in a breaker and a half scheme [23]. The actual CT connections used in each CT scheme and associated protection philosophies are explained by a practicing engineer in [23].

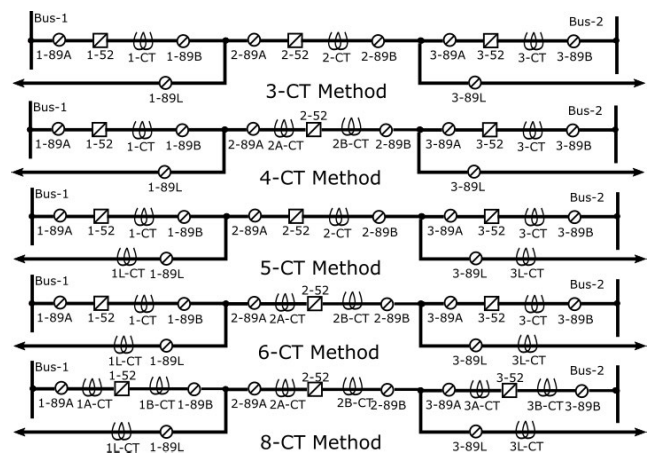


FIGURE 8. Breaker and a half scheme: Possible CT arrangements.

The required number of 0.2 class and PS class CT secondary cores in each CT arrangement of the breaker and a

half scheme are shown in Table.2. The minimum number of CT cores required, excluding those used for backup (Main-2), are tabulated. From Table.2, it is evident that a maximum of 5 cores, at least one metering core of 0.2 class and 4 PS class cores, are needed per bay for realizing all the CT arrangements. The same analysis is performed for the double breaker double bus and the ring bus configurations. It is found that one and a half breaker scheme CT requirements will meet all the other bus bar arrangements. The developed substations are intended to be used with 3- ϕ , 5 kVA, 220 V micro-alternators present in the lab. Selecting a customized five/three core CT of a low current rating (20 A/1 A) will restrict the replacement possibility in the future. Hence, custom-designed single-phase single-core PS class, and 0.2 class CTs manufactured by a local vendor are used in the panel. Open-type CTs with top connections are designed to facilitate easy replacement and re-wiring.

TABLE 2. Number of secondary cores—breaker and a half.

CT Method	Bay-1		Bay-2		Bay-3		LINE-1		LINE-2	
	0.2	PS	0.2	PS	0.2	PS	0.2	PS	0.2	PS
3-CT	2	2	2	1	2	0	0	0	0	0
4-CT	1	2	2	3	1	2	0	0	0	0
5-CT	1	2	1	2	0	2	1	2	1	2
6-CT	1	2	2	3	1	2	1	2	1	2
8-CT	1	4	2	2	1	4	1	2	1	2
Max.cores/CT	1	4	2	3	1	4	1	2	1	2
Max.Cores/Bay	5		5		5		3		3	

The single line diagram in Fig.9 shows the placement of CTs and PTs in Bay-1. The figure also shows the internal components mounted inside the GPSA front side. It can be observed that all the elements from top to bottom in the one-line diagram are placed bottom-up in the panel. Each bus is realized using three copper bus bars of 450 A, 415 V ratings. For each CB, provision is made to place three cores (1-0.2class, 2-PS class) on the top/left side and five cores (1-0.2 class, 4-PS class) on the bottom/right side. Also, provision is made to place five cores (1-0.2 class and 4-PS class) below the line isolators (89L) for feeders. However, only the number of cores shown in the Table.2 are populated in the manufactured panels. Independent PTs, with two secondary cores (1-3P class and 1-0.2 class), are provided for three bus bars and the feeder connection points.

D. TOPOLOGY CONNECTION PANEL

The developed laboratory contains physical machines to emulate power plants, RLC passive loads, scaled-down passive transmission lines, power electronic emulated transmission lines, and loads. All these stays in different rooms of the laboratory. The outputs of all these elements are gathered at one panel called a topology connection panel. From all the six substations, 24 feeder connections are also brought to this panel. The researchers can connect desired network topology using this panel. Fig.10 shows the developed topology panel. It consists of four verticals; the first (from left to right) and the last verticals bring outputs of ten sources and ten loads.

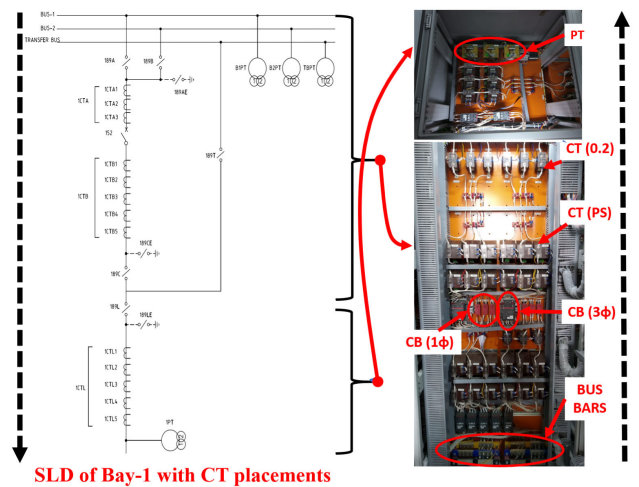


FIGURE 9. Components in GSPA panel.

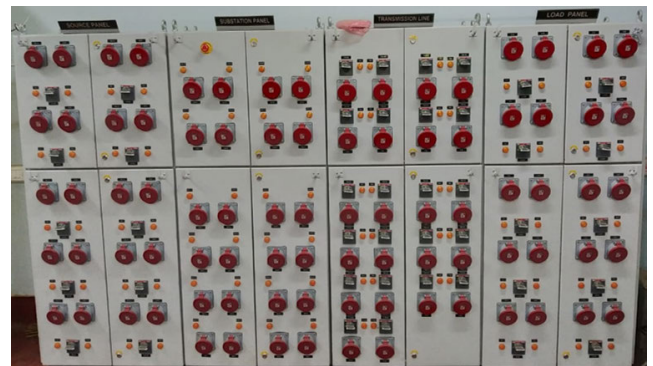


FIGURE 10. Topology connection panel.

Observe that each generator/load has two sockets. One socket can be used for connecting to other network elements, and the second socket can be used for creating faults at the bus. A point on wave IGBT-based fault creator is also developed for this purpose [25]. The second vertical brings all the six substation feeder connections, four connections per substation. The third vertical gathers the outputs of 11 transmission lines, two sockets for each end of the line. Patch cards are provided for making the topology connections.

IV. RECONFIGURATION OF THE GENERALIZED SUBSTATION PANEL

Using the SS CONFIG selector switch on GSPA one can configure the GSP for any desired bus-bar arrangement. When a user selects the desired substation configuration in the SS-CONFIG selector switch, the isolators, CBs, and earth switches in some of the bays must be permanently open to realize the selected configuration, and they form the un-energized circuit in the GSP. However, some of the isolators, CBs, and earth switches in the bays should be allowed to operate in local and remote modes adhering to their interlock policies, and a few of them should be permanently closed

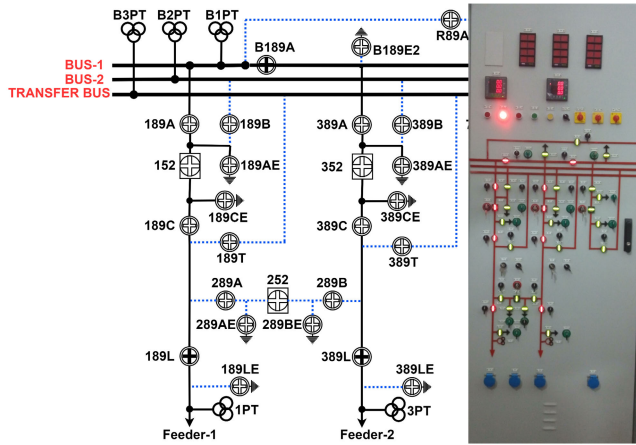


FIGURE 11. SS CONFIG option-1: Single bus-single breaker.

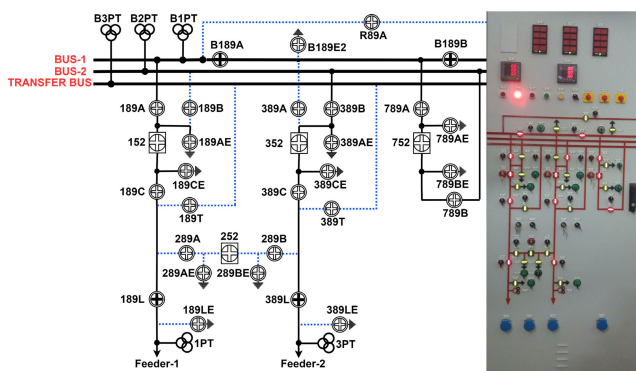


FIGURE 12. SS CONFIG option-2: Double bus-single breaker.

to realize the selected configuration. These elements form the energized circuit in the GSP. For each SS-configuration, the isolators, CBs, and earth switches in the panel are classified into three subsets: *inhibited to-open subset (IHO)*, *inhibited to-close (IHC) subset*, and *operational subset (OP)*. The isolators, CBs, and earth switches classified into IHO and IHC subsets for all the seven widely used substation configurations discussed are listed in Table.3; The components not listed in the Table.3 for each configuration constitute the corresponding OP-subset. The IHC subset forms the un-energized circuit for a given configuration. IHC and OP subsets form the corresponding energized circuit of the selected configuration.

The figures Fig.11 - Fig.16 show partial sections of the SLDs of the proposed substation configured for different station arrangements. The figures also contain the pictures showing the results after configuring the GSP to the corresponding bus bar configuration. The solid thick lines in the SLDs represent the energized circuit of the selected bus bar configuration. The dotted lines represent the circuit that is not in use for that configuration (un-energized circuit). In the figures, black color filling is used in the isolator/CB '+' symbols to indicate a permanently closed condition for the selected configuration. The red and the green semaphore

indicators on the MIMIC of the pictures show the energized and the un-energized paths after the GSP is configured with the selected configuration. Special control logics are developed to achieve the reconfiguration features in local (manual) and remote modes (using SCADA/BCU/IED).

A. SINGLE BUS SINGLE BREAKER

The single-bus-single-breaker (SBSB) configuration is widely used at lower transmission voltage levels and plant auxiliary supplies. It is the most basic, economical, and straightforward bus configuration. This arrangement does not provide operating flexibility, and any breaker problem/maintenance requires circuit de-energization. If the SS CONFIG selector switch on GSPA is set to option-1 then all the feeders in the GSP will be configured for this station arrangement. The resulting connection diagram for feeder-1 and feeder-2 in the GSP is shown in Fig.11.

In GSP, only Bus-1 will be used for energization in this configuration. All the sections of Bus-1 will be connected by closing B189A, B189B, and B189C isolators and they should be inhibited from opening. In Bays 1,3,4 and 5, the bus-2 isolators 89B, transfer bus isolators 89T should be inhibited from closing both in manual and remote modes. The CBs and isolators in Bays 2, 5, 7 and 8 also should be completely inhibited to close. The result after GSP is configured to SBSB can be seen in the picture, see Fig.11. One can observe the energized circuit (the red strips) and the un-energized circuit (green strips) using the semaphore indicators.

B. DOUBLE BUS SINGLE BREAKER

Double-bus-single-breaker with tie CB (DBSB) can be achieved by selecting option-2 in the SS CONFIG selector switch. For this case, Bay-7 CB (7-52) performs the bus-coupler (Tie CB) operation, as shown in Fig.12. In this configuration, feeders can be connected to a specific bus at any given time. In Fig.12, it can be observed that Feeder-1 is connected to Bus-1, and Feeder-2 is connected to Bus-2. The tie CB is used to equalize potentials between the two buses before transferring one feeder from one bus to the other [22]. The developed PLC logic inhibits the operation of the un-energized circuit. The result after GSP is configured in DBSB can be observed from the picture in Fig.12.

C. MAIN AND TRANSFER BUS AND DOUBLE BUS SINGLE BREAKER WITH TRANSFER BUS

Operating flexibility is further increased by the addition of a transfer bus to a SBSB or DBSB. Main and transfer bus (MTB) operation of this is similar to SBSB configuration, with all circuits supplied from the main bus. Transfer bus is useful only when any circuit breaker is out of service or requires maintenance. Only one circuit can be connected to the transfer bus at any time.

Fig.13 shows the connection diagram for MTB realization using the GSP. Option-3 in the selector switch will configure this arrangement. In this case, Bus-1 is the main bus, with all sections closed, to which all the four feeders are

TABLE 3. Status of isolators, earth switches and circuit breakers in the generalized substation model.

Configuration	Bay No	Inhibited to open		Inhibited to close		
		Isolators	CBs	Isolators	Earth switches	CBs
SBSB	Bay-1&2	189L	-	189B, 189T, 289A, 289B	289AE, 289BE, 189LE	252
	Bay-3&7	389L	-	389B, 389T, 789A, 789B	789AE, 789BE, 389LE	752
	Bay-4&5	489L	-	489B, 489T, 589A, 589B	589AE, 589BE, 489LE	552
	Bay-6&8	689L	-	689B, 689T, 889A, 889B, 889T	889AE, 889TE, 689LE	852
	Bus bars	B189A, B189B, B189C	-	R89A	B189E2, B189E3, B289E1, B389E1	-
DBSB	Bay-1&2	189L	-	189T, 289A, 289B	289AE, 289BE, 189LE	252
	Bay-3&7	389L	-	389T	389LE	-
	Bay-4&5	489L	-	489T, 589A, 589B	589AE, 589BE, 489LE	552
	Bay-6&8	689L	-	689T, 889A, 889B, 889T	889AE, 889TE, 689LE	852
	Bus bars	B189A, B189B, B189C	-	R89A	B189E2, B189E3, B389E1	-
MTB	Bay-1&2	189L	-	189B, 289A, 289B	289AE, 289BE, 189LE	252
	Bay-3&7	389L	-	389B, 789A, 789B	789AE, 789BE, 389LE	752
	Bay-4&5	489L	-	489B, 589A, 589B	589AE, 589BE, 489LE	552
	Bay-6&8	689L	-	689B, 889B	689LE	-
	Bus bars	B189A, B189B, B189C	-	R89A	B189E2, B189E3, B289E1	-
DMTB	Bay-1&2	189L	-	289A, 289B	289AE, 289BE, 189LE	252
	Bay-3&7	389L	-	-	389LE	-
	Bay-4&5	489L	-	589A, 589B	589AE, 589BE, 489LE	552
	Bay-6&8	689L	-	-	689LE	-
	Bus bars	B189A, B189B, B189C	-	R89A	B189E2, B189E3	-
BH	Bay-1&2	-	-	189B, 189T	-	-
	Bay-3&7	-	-	389A, 389T, 789A, 789B	789AE, 789BE	752
	Bay-4&5	-	-	489B, 489T	-	-
	Bay-6&8	-	-	689A, 689T, 889A, 889B, 889T	889AE, 889TE	852
	Bus bars	B189A, B189B, B189C	-	R89A	B189E2, B189E3, B389E1	-
DBDB	Bay-1&2	289A, 289B	252	189B, 189T	289AE, 289BE	-
	Bay-3&7	-	-	389A, 389T, 389L, 789A, 789B	389LE, 789AE, 789BE	752
	Bay-4&5	589A, 589B	552	489B, 489T	589AE, 589BE	-
	Bay-6&8	-	-	689A, 689T, 689L, 889A, 889B, 889T	689LE, 889AE, 889TE	852
	Bus bars	B189A, B189B, B189C	-	R89A	B189E2, B189E3, B389E1	-
RB	Bay-1&2	-	-	189B, 189T	-	-
	Bay-3&7	389A, 389C	352	389B, 389T, 789A, 789B	789AE, 789BE	752
	Bay-4&5	-	-	489B, 489T	-	-
	Bay-6&8	689A, 689C	652	689A, 689T, 889A, 889B, 889T	889AE, 889TE	852
	Bus bars	B189B, R89A	-	B189A, B189C	B289E1, BT89E1	-

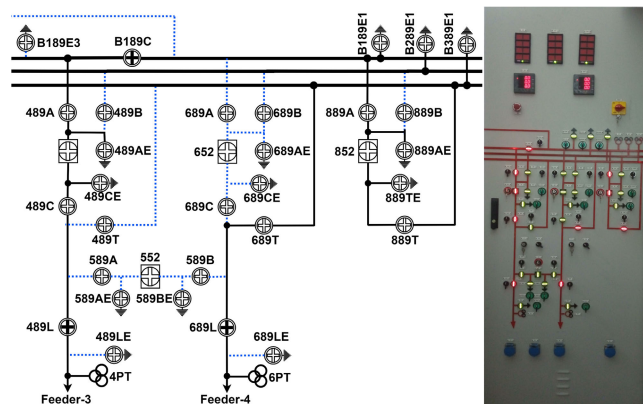


FIGURE 13. SS CONFIG option-3: Main and transfer bus.

connected. Bus-2 is not part of this configuration. A software configurable option is also provided in the PLC to select the Double main and transfer bus Scheme (DMTB) using the selector switch Option-3. Bus-2 isolators 89B of all the feeders and bus coupler bay-7 should be allowed to close to achieve DMTB. The picture in Fig.13 shows the result after the GSP is configured in MTB bus bar arrangement.

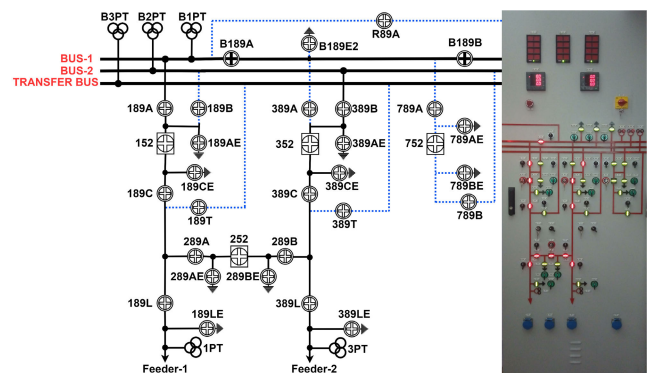


FIGURE 14. SS CONFIG option-4: Breaker and a half.

D. BREAKER AND A HALF

Breaker and a half (BH) configuration provides improved operating flexibility. It is extensively used in 400 kV high voltage substations of the country. Each feeder section is supplied by two buses through two circuit breakers. The center CB serves both the feeders [24]. Fig.14 shows the connection diagram. SS CONFIG option-4 will configure this arrangement. Feeders 1 & 3 should be connected to bus-1, and Feeders 2 & 4 should be connected to bus-2. CB 252 acts as

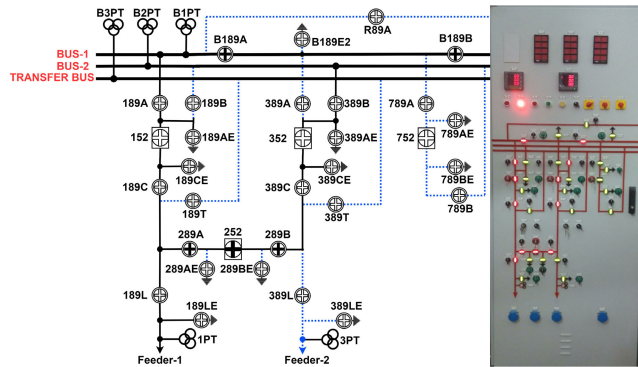


FIGURE 15. SS CONFIG option-5: Double bus–double breaker.

the common CB between the feeders 1 & 2. Similarly, the CB 552 acts as the common CB between the feeders 3 & 4. Feeder-1 to Bus-1, Feeder-2 to Bus-2, and CB 252 closed connections can be observed in the figure. The result after the GSP is configured in BH arrangement can be observed in the picture as well.

E. DOUBLE BUS–DOUBLE BREAKER

This is a widely used configuration in 765 kV and higher voltage substations of the country. The Double bus double breaker (DBDB) configuration serves each feeder through two dedicated CBs. Option-5 in the SS CONFIG will configure the GSP to DBDB. Fig.15 shows the connection diagram and the picture. Only two feeders (feeder 1, 3) can be used in this scheme by default. It can be observed in Fig.15 that only Feeder-1 is shown as active. Bay-2 & 5 should be permanently closed, and PLC logic inhibits them from opening. The picture in Fig.15 shows the result after the GSP is configured in DBDB arrangement.

F. RING-BUS

This is a popular bus bar arrangement in high voltage networks with one CB serving two feeders. This configuration is achieved by option 6 in the SS CONFIG selector switch. Fig.16 shows the connection diagram to achieve the ring bus configuration and the corresponding results in the picture. The bus-1 section isolators B189A and B189C should be permanently opened. The ring bus isolator R89A and the bus-1 section isolator B189B should be permanently closed. Bay-3 and Bay-6 also need to be permanently closed.

V. ISOLATOR, EARTH SWITCH, AND CIRCUIT BREAKER CONTROL LOGIC IMPLEMENTATION

In this section, the control logics implemented to achieve isolator, earth switch, and circuit breaker operations both in local and remote modes, just like how they operate in the physical substation, are described.

A. ISOLATOR CONTROL LOGIC

Fig.17 shows the wiring diagram for the control logic implementation used for isolators in the panel. Three auxiliary contactors labeled as X89XCx, X89XTx, and X89XAx

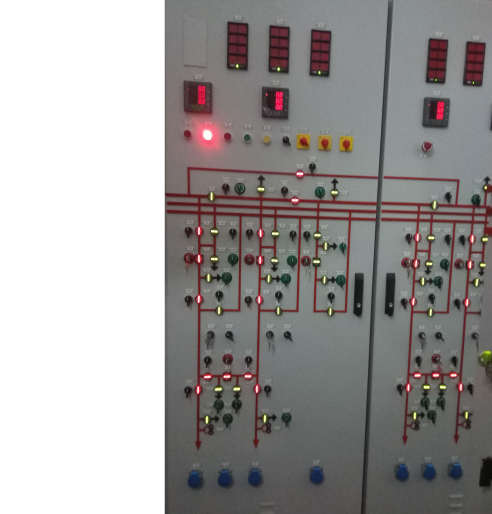
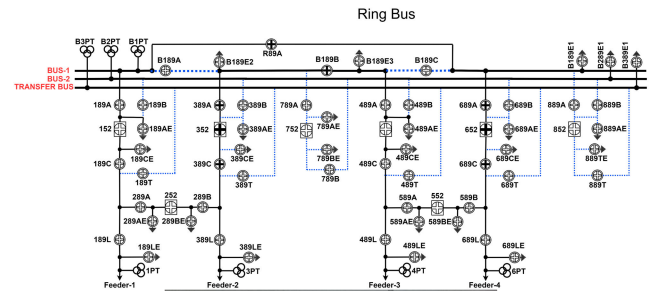


FIGURE 16. SS CONFIG option-6: Ring bus.

are provided for closing operation, tripping operation, and mimicking the status of the power contactor, respectively (corresponding to each isolator power contactor labeled X89XP-ISOLATOR). The ‘X’ before and after the symbol ‘89’ can be replaced to represent the isolators corresponding to the CBs of different bays shown in Fig.2. Multiple normally open ‘NO’ and normally closed ‘NC’ contacts are made available for all the auxiliary and power contactors. One NO contact is used for X89XCx labeled as “X89XCx CLOSE CMD” for capturing the close command signal. One NC contact is used for X89XTx labeled as “X89XTx TRIP CMD” for capturing the trip command signal, and three NO contacts are used for X89XAx, labeled as “X89XAx SELF LATCH”, “X89XAx PLC STATUS” and “X89XAx INDICATION”. An auxiliary contactor labeled “Interlock from PLC” is used to implement the received commands from the PLC. TNC switch is a spring-activated switch that automatically brings back the switch position to the normal position from the other two positions. The three positions of TNC switch labeled as ‘T’ for trip command, ‘C’ for close command and ‘N’ for no operation, two positions of Local/Remote (L/R) switch labeled as ‘LOCAL’ and ‘REMOTE’ and six positions of “SS CONFIG” switch are wired as input to the PLC. The isolator can be closed or opened manually using a TNC switch or remotely using a bay control unit (BCU).

1) ISOLATOR CLOSING AND OPENING OPERATION

The closing operation is explained for the L/R switch set in ‘Local’ position using the two paths (1) and (2) shown

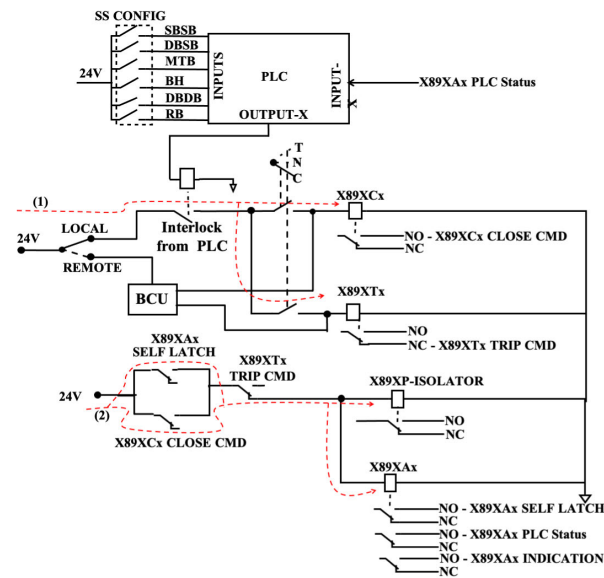


FIGURE 17. Isolator control logic wiring implementation.



FIGURE 18. Inhibited to open (IHO) subset control logic implementation in PLC for isolator.

with dashed arrows in Fig.17. Path (2) is also valid for the L/R switch set in the ‘Remote’ position. The selected station configuration will be reflected at the input to PLC as logic ‘1’ from the status of the SS CONFIG switch. If the isolator belongs to IHC-subset, the PLC is programmed to make Output-X always ‘0’ for the chosen configuration. As a result, the auxiliary contactor “Interlock from PLC” remains open. If the isolator belongs to IHO-subset, then the PLC is programmed to follow the ladder logic diagram shown in Fig.18. In the ladder logic, the symbol with two vertical lines shows that the signal status is taken as-is, and an inverted N symbol shows the NOT operation of the corresponding signal. If the isolator belongs to OP-subset, then the PLC should be programmed to follow the ‘Isolator-Earth Switch-Circuit Breaker Interlocks’ as per the operational practices of the utility. When the PLC Output-X becomes ‘1’, the contactor ‘Interlock from PLC’ gets closed.

Path (1): The contact ‘LOCAL’, ‘Interlock from PLC’ and ‘C/T’ contact of TNC switch are wired in series in this Path. The contactor ‘LOCAL’ gets closed when option-1 is selected in ‘L/R Switch’ for local operation. When the ‘Interlock from PLC’ is closed, the auxiliary contactors X89XCx/X89XTx get energized when a CLOSE/TRIP command is issued from the TNC switch. ‘Interlock from PLC’ gets closed as per the logic described for the subset (IHC, IHO or OP) to which the isolator belongs.

Path (2): One can observe another 24 V path going to the power contactor “X89XP-ISOLATOR” and ‘X89XAx’

auxiliary contactor. In this Path, a parallel combination of ‘X89XAx SELF LATCH’ and ‘X89XCx CLOSE CMD’ is in series with ‘X89XTx TRIP CMD’. Observe that the NC contact of the ‘X89XTx TRIP CMD’ is used here. Since the auxiliary contactor ‘X89XTx’ is a normally open type, the NC contact by default will close the 24 V path to energize the power contactor and ‘X89XAx’ as soon as the ‘X89XCx CLOSE CMD’ contact gets closed in Path (1) by a CLOSE command. Then the ‘X89XAx SELF LATCH’ contact will make a parallel path for 24V to the power contactor and its auxiliary contactor. Now, if a TRIP command is given from the TNC switch, then 24V gets disconnected in Path (2), then the isolator power contactor and the auxiliary contactor will get de-energized.

In Fig.18, SS CONFIG switch input and NOT of “X89XAx PLC STATUS” are kept in series to create IHO-subset logic for isolator. The status of “X89XAx PLC STATUS” will be ‘0’ by default as it is a normally open contact of the auxiliary contactor and because of NOT operation used, the ladder logic shown in the figure will make the PLC Output-X as ‘1’. So initially, the contactor ‘Interlock from PLC’ will be closed, the X89XCx gets energized, and the NO contact ‘X89XCx CLOSE CMD’ will be active when a CLOSE command is given from the TNC switch in Path (1). This will energize the power contactor and ‘X89XAx’ in Path (2). Then all the three NO contacts used for the X89XAx will be closed. The Output-X of the PLC will become immediately zero due to NOT operation used for the status contact ‘X89XAx PLC STATUS’, and hence the ‘Interlock from PLC’ will be opened. Even if someone gives a TRIP command after the isolator is closed, the Path (1) will not get 24 V supply, and hence the isolator will be inhibited to open once it is closed if the isolator belongs to IHO-subset.

B. EARTH SWITCH CONTROL LOGIC

No physical power contactor is used for the earth switch in the developed panel. Its operation is emulated using auxiliary contactors to mimic the physical earth switch operation philosophy.

1) EARTH SWITCH CLOSING AND OPENING OPERATION

Fig.19 shows the earth switch control logic implemented in the panel. An Auxiliary contactor labeled as ‘X89XEx’ is used to mimic the earth switch operation. The ‘X’ before and after symbol ‘89’ can be replaced to represent the earth switches associated with the pair of isolators corresponding to the CBs of different bays shown in Fig.2. One can observe from the figure that the ‘LOCAL’ contact of ‘L/R Switch’, the parallel combination of ‘C’ contact of TNC switch and ‘X89XEx SELF LATCH’, the ‘NC’ contact of ‘T’ contact of TNC Switch, and the contact ‘Interlock from PLC’ are connected in series. When the TNC switch gives a close command in local mode, the earth switch gets energized as long as the ‘Interlock from PLC’ is closed by the PLC Output-Y. Immediately after closing the earth switch ‘X89XEx’, its ‘X89XEx SELF LATCH’ contact will keep the earth switch

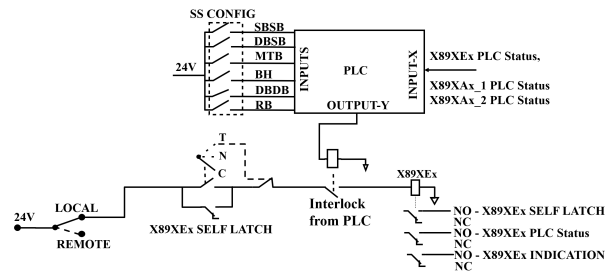


FIGURE 19. Earth switch control logic wiring implementation.



FIGURE 20. Earth switch and isolator interlock logic implementation in PLC.

energized even after the TNC switch is reset to a normal position. When a trip command is given from the TNC switch, the earth switch gets de-energized since the ‘NC’ contact of ‘T’ gets opened. The PLC Output-Y, which decides the status of the ‘Interlock from PLC’ follows the ladder logic shown in Fig.20. In this ladder logic, the NOT of the status signals of the auxiliary contactors mimicking the pair of isolators associated with the circuit breaker is connected in series. So, only if the pair of isolators are in an open position, the Output-Y will be ‘1’, which closes the ‘Interlock from PLC’ contactor. This way, the isolator-earth switch interlocks used in practical substations are achieved.

C. CIRCUIT BREAKER CONTROL LOGIC

Three-phase and single-phase power contactors used for mimicking gang operation and independent pole operation of the circuit breakers need to be operated in both the local and remote mode as they are operated in the physical substation.

1) CIRCUIT BREAKER CLOSING AND TRIPPING OPERATION

Fig.21 shows the wiring implementation used in the panel for circuit breaker control logic. As mentioned earlier, provision for 3-pole and 1-pole operation of CBs is made available. The contactors labeled X52P - 3PH CB, X52P - R - CB, X52P - Y - CB, and X52P - B - CB, right side bottom corner of the figure, represents the power contactors of the 3-phase CB, R - phase CB, Y - phase CB and B - phase CB respectively. Auxiliary contactors labeled X52Cx and X52Tx, right side top corner of the figure, are used to capture CLOSE, and TRIP commands respectively from LOCAL/REMOTE modes to close/trip all the three phases of both the single-phase and the three-phase CBs. An Auxiliary contactor labeled X52Pro-Tx is used to capture trip command signals from protection relays for 3-phase CB. The auxiliary contactors labeled X52TxR, X52TxY and X52TxB are used to capture the trip command signal for single-phase breakers in R, Y, and B phases, respectively in REMOTE mode from the protective relays. The ‘X’ before the symbol ‘52’ can be replaced to

represent the CBs of different bays shown in Fig.2. In Fig.21, the paths (1) to (5) shown with dotted arrows are used to explain the CB control logic.

Path (1): In this path, ‘LOCAL’ contact of ‘L/R Switch’ & ‘C’ contact of TNC switch are connected in series to the auxiliary contactor ‘X52Cx’ through synchronization command ‘SYNC OK’. The ‘SYNC OK’ signal can be issued from a synchronizing trolley in local mode and from SCADA/BCU in remote mode. When a close command is issued from the TNC switch, X52Cx gets energized and four ‘NO’ contacts, ‘X52Cx 3PH - CB Close CMD’, ‘X52Cx 1PH - R - CB Close CMD’, ‘X52Cx 1PH - Y - CB Close CMD’ and ‘X52Cx 1PH - B - CB Close CMD’, which are used to close the power contactors of 3-phase and single phase CBs in path (4) and (5), will be closed. Also, observe that the ‘T’ contact of the TNC switch and the auxiliary contactor ‘X52Tx’ are connected in series. When a trip command is given from the TNC switch, then ‘X52Tx’ gets energized and four ‘NC’ contacts, ‘X52Tx TRIP 3PH - CB’, ‘X52Tx TRIP 1PH - R - CB’, ‘X52Tx TRIP 1PH - Y - CB’, ‘X52Tx TRIP 1PH - B - CB’, which are used to trip the power contactors in path (4) and (5), will be opened. One can also observe the ‘Pole discrepancy protection INTERLOCK FROM PLC’ contact parallel to the TNC switch ‘T’ contact. This signal logic is created in PLC for tripping the CBs in case of any pole discrepancy is observed. In remote mode, this logic needs to be created in ‘BCU’.

Path (2): In this path, ‘REMOTE’ contact of the ‘L/R Switch’ is connected in series with ‘X52Cx’ through two sub-paths. In one sub-path, ‘CB Close CMD’ and ‘SYNC OK’ are in series. In another sub-path, ‘Auto Reclose CMD’ is in series. The above commands will be issued from a BCU in remote mode for manual CB closing and an IED for auto reclosing operation. A synchronizing relay or a BCU issues the ‘SYNC OK’ if the CB terminals meet the synchronization conditions. It is to be noted that for auto reclosing operation, ‘SYNC OK’ is not used in series. This will be checked within the BCU/IED. The ‘REMOTE’ contact in series with ‘X52Tx’ can also be observed in a third sub-path through ‘MANUAL TRIP 3 PH’ contact, which will be controlled through a BCU for issuing the manual trip command for 3-phase CB in remote mode.

Path (3): This path is essentially comprised of four sub-paths. Except for the first one, all the remaining paths have identical structure. ‘REMOTE’ contact of the ‘L/R Switch’ is connected in series to all the sub-paths. In the first sub-path, an auxiliary contactor ‘X52Pro-Tx’ is in series with a contactor labeled ‘PROTECTION TRIP 3PH’. The latter gets activated whenever a TRIP command is issued from any protective relay to trip the 3-phase breaker. So following a protection trip command in remote mode, ‘X52Pro-Tx’ gets energized and the corresponding ‘NC’ contact labeled ‘X52Pro-Tx - PROT TRIP 3PH - CB’ will be opened, which is used in the path (4) for tripping the power contactor of 3-ph CB. The remaining three sub-paths operation is similar to the first path and they are used for tripping logic implementation

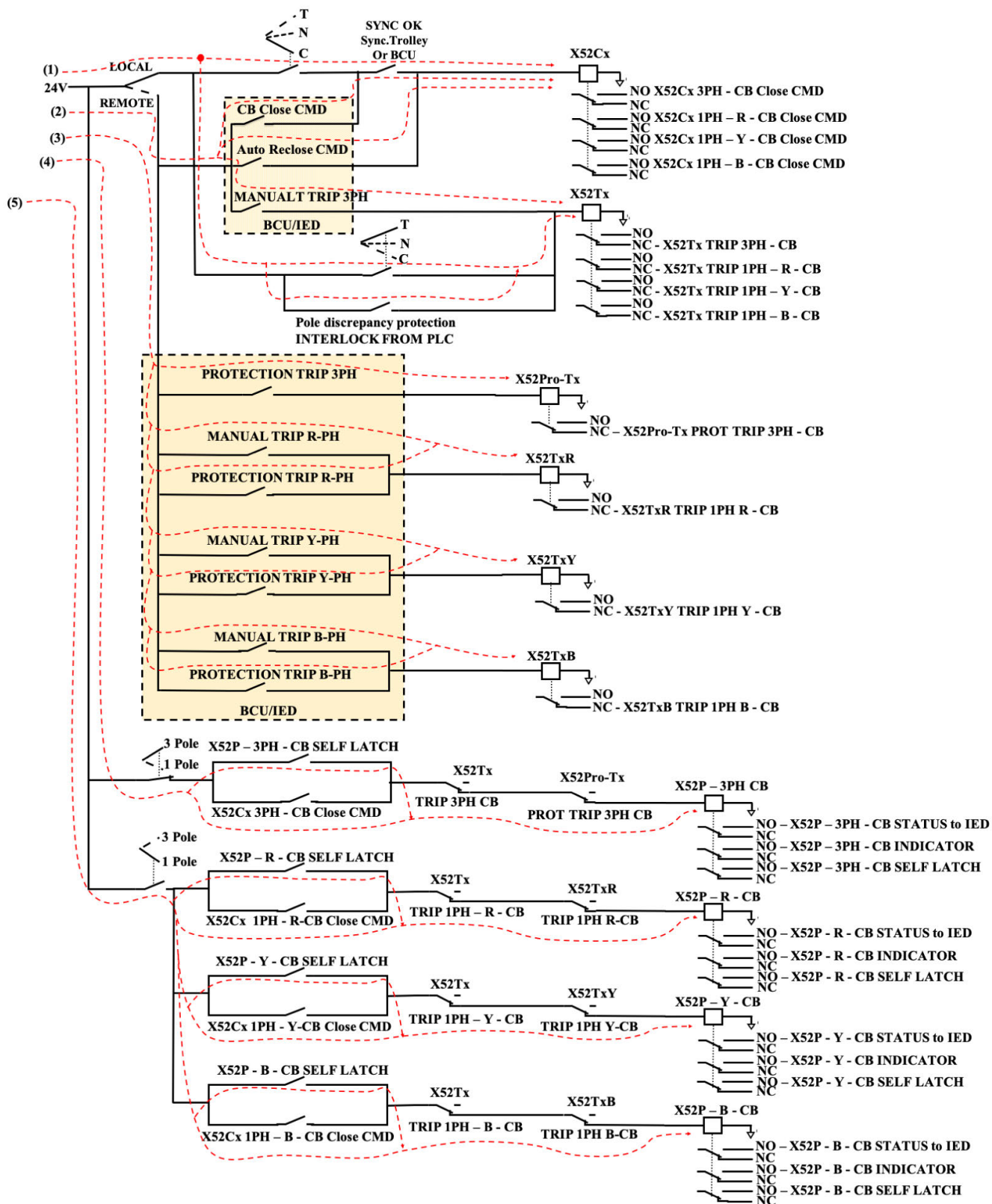


FIGURE 21. Circuit breaker control logic wiring implementation.

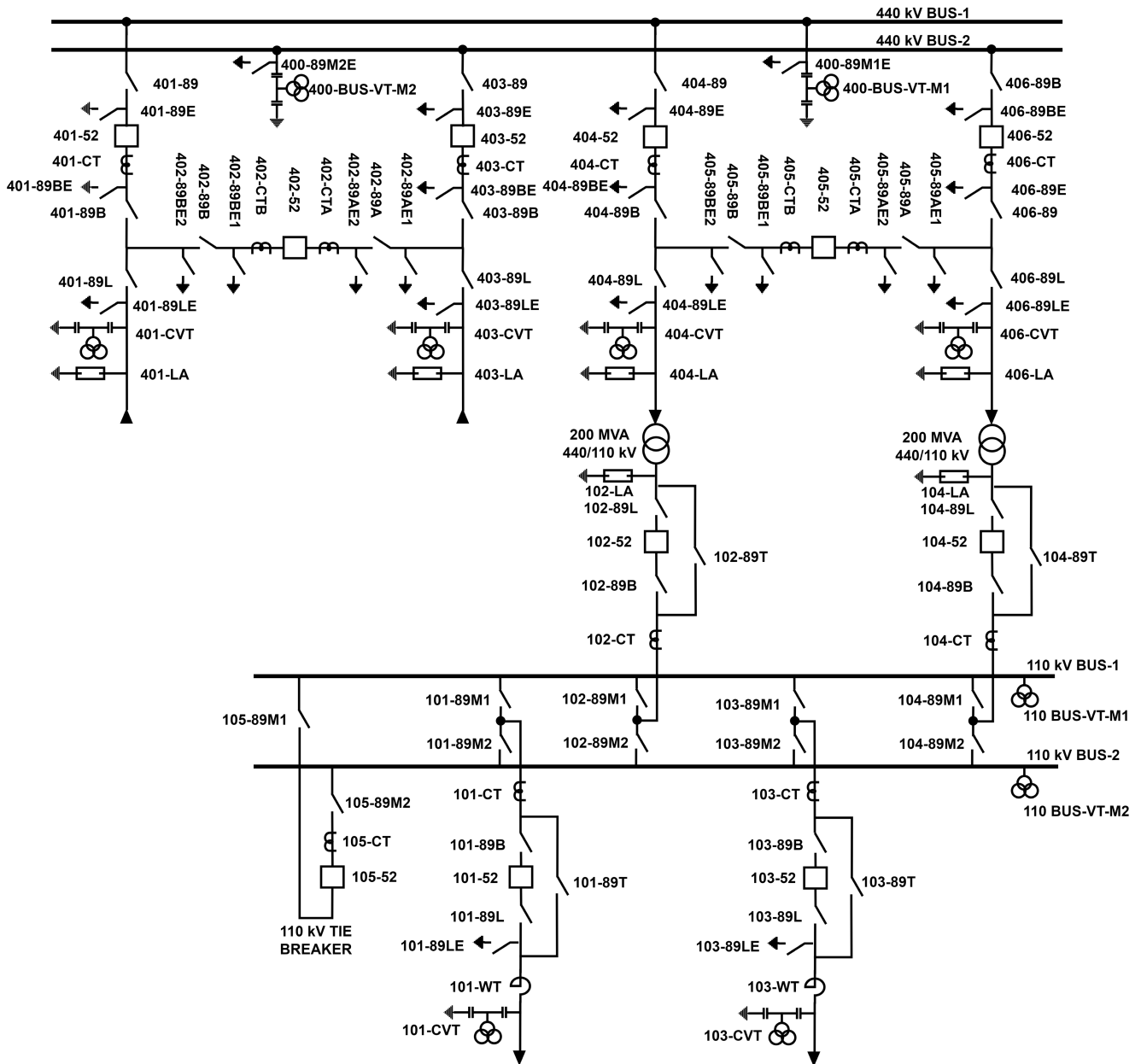


FIGURE 22. Typical 440 kV/110 kV substation single line diagram.

for the R, Y, and B phases of the single-phase CBs. However, in these three paths, the manual trip command contacts which get activated when a trip command is issued from BCU for the respective phases (for example, ‘MANUAL TRIP R-PH’) are also used in parallel to the protection trip command contact from IED. A single auxiliary contactor captures both the manual (from BCU) and protection trip commands for single-phase CBs. However, for 3-phase CB manual trip and protection trips are covered separately in path (2) and path (3), respectively.

Path (4) and Path (5): These two paths are similar in structure. Path (4) is used for closing or tripping of the power contactor ‘X52P - 3PH CB’ of the 3-phase CB. Path (5)

with three sub-paths is used for closing and tripping of the power contactors ‘X52P - R - CB’, ‘X52P - R - CB’ and ‘X52P - R - CB’ of the single-phase CBs in R, Y and B phases respectively. Path (4) will be active if the 3-pole option is selected in the ‘3-Pole/1-Pole’ switch and path (5) will be active if the 1-pole option is selected in the switch. It can be observed that ‘NO’ contact of the power contactors used for ‘SELF LATCH’ are connected in parallel to the close command contacts corresponding to the 3-phase and single-phase CBs discussed in path (1) and (2). One can also observe two ‘NC’ contacts of the trip command contacts, discussed in path (2) for the manual trip and path (3) for protection trip, in series with the above parallel combination. Since the

substations can be used to conduct advanced research on wireless and wired communication systems, protocols and cyber security aspects.

- Cascade event scenarios generation using breaker failures, technical and hidden failures of relays, the impact of auto-reclosing, delayed fault clearing, etc.
- Experimental validation of restoration strategies carried out on the developed test bed.
- Control center algorithms on topology processing, static and dynamic state estimation, predictive, corrective, and emergency controls.
- Realistic field data generation, metering, and protection class data, using field devices such as fault recorder, PMU, relay, SER, etc., for data analytics and artificial intelligence applications.

The realization of an actual 440 kV/110 kV substation using the developed generalized substation panels is described below. Fig.22 shows a typical single line diagram of a 440 kV/110 kV substation in India. There are two different bus-bar arrangements used in this station. One is a breaker and half configuration for 440 kV side and the other is a double bus single breaker with a tiebreaker configuration for 110 kV side. There are two incoming transmission lines in the 440 kV side and two outgoing connections to the HV side of the two 440 kV/110 kV transformers. In the 110 kV side of the substation, there are two incoming connections to the LV side of the two 440 kV/110 kV transformers and two outgoing 110 kV sub-transmission lines.

This substation can be realized in the laboratory by using two GSPs as shown Fig.23. Here one GSP with 4 feeders is used for 440 kV side. Another GSP with 4 feeders is used for 110 kV side realization. Two feeders of these GSP models can be connected through 1:1 transformers to represent the interconnection between the 440 kV and 110 kV voltage levels in the reference substation. Even if the number of feeders in each network is more than four, multiple GSP models can be interconnected to realize the larger number of feeders. This way any large substation having multiple voltage levels can be implemented in the laboratory using one or more GSPs.

VII. CONCLUSION

This paper introduced a unique realistic scaled-down generalized substation model for smart grid research and education in the laboratory. The proposed substation model can be reconfigured to achieve any practical bus bar configuration and associated CT arrangements. An approach for obtaining different bus bar arrangements in a single substation has been discussed. Circuit breakers and associated isolators are emulated using contactors. Provision for gang operation and single-pole operation of the CBs is provided. The interlock logics followed in the field have been implemented to mimic a realistic substation operation in the laboratory. A topology connection panel is designed to enable the realization of different power system topologies. Six substation panels, with four feeders (65 A, 415 V capacity) per panel, have been installed in the laboratory. Detailed description of the

reconfiguration features and control logics used in the implementation is provided. The proposed design is targeted to bridge the gap between field practices and academic research. The proposed generalized substation model would enable the researchers to experiment and validate most of the research outcomes, which cannot be practically verified in real power systems. The authors hope that these facilities at research institutions will increase the credibility of academic research and enable faster adoption of technologies by the industries.

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