Fundamentals of Microgrid Dead Bus Arbitration

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FUNDAMENTALS OF MICROGRID DEAD BUS ARBITRATION

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Abstract—A microgrid is a smaller electric network that can operate independently of a main power grid. An islanded microgrid is typically energized by a generator or inverter and the closing of its associated circuit breaker into a dead bus. A synchronism check is a typical function of programmable protective relays (PPRs) that supervise the closing of these breakers. The source's voltage and frequency must be in synchronism with the bus voltage prior to closing this breaker. However, in an islanded microgrid energization scenario, a synchronism check cannot be achieved when the bus voltage is dead. Protective relays that attempt to close into a dead bus cannot differentiate between a failed potential transformer (PT) supply and a true dead bus condition. A failed PT supply presents itself as a dead bus voltage condition to the protective relay controlling the generator or inverter breaker. This can create a potentially hazardous situation when a protective relay might close a live machine's breaker into a live bus that is out of synchronism. This paper explains the problem associated with dead bus arbitration and the various failure modes of PT voltages that necessitate a dead bus arbitration scheme. Typical microprocessor PPR solutions for dead bus close supervision of synchronization systems are also presented. In addition, this paper discusses a scenario with an inverter-based resource (IBR) energizing a dead bus and limitations that need to be considered.

Index Terms—Microgrid, synchronizing, dead bus, protection and control

I. INTRODUCTION

Modern microgrids are provided with internal generation that can be of many different types. These generation types are referred to as distributed energy resources (DERs) in most literature. Whether rotating generators or inverter-based resources (IBRs) are involved, closing the source breaker (or in some cases, the step-up transformer breaker) to link to the microgrid has certain considerations that are the focus of this paper. Closing a breaker that has a very large angular or magnitude difference across its contacts can lead to catastrophic consequences [1].

IBRs, such as battery energy storage systems (BESSs), present additional challenges when energizing a dead bus. These resources typically ramp the bus voltage from zero to nominal in an effort to limit inrush associated with transformer magnetization and cold load pickup. A solution to these challenges is discussed in this paper.

Fig. 1 shows a simple microgrid example that illustrates the importance of verifying the conditions across a microgrid breaker before closing.

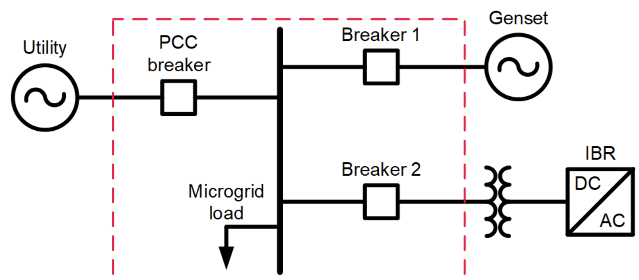

Fig. 1 Microgrid and Internal Sources

The load in the microgrid is served by the internal generation (a generator set [Breaker 1], also called a genset, and an IBR [Breaker 2]) and the link to the utility though the point of common coupling (PCC). The PCC breaker determines whether the microgrid is grid-tied or islanded. When grid-tied, the utility is the largest source determining the voltage and frequency of the microgrid. When islanded, the genset and IBR share the load using a droop frequency and voltage control strategy [2].

The transition from islanded to grid-tied requires the closing of the PCC breaker. For the condition in which both the microgrid and the utility are energized, the difference in magnitude and phase across the breaker needs to be checked before closing. It is also possible to encounter the following conditions on the two sides of the PCC breaker:

- A dead microgrid and a live utility. This implies that there is no internal generation in the microgrid.
- A dead utility and a live microgrid. This implies that the main grid is not available and that there is generation in the microgrid.
- A dead utility and a dead microgrid. Most likely, this condition is experienced during commissioning, where certain parts of the installation are not available.

A dead bus can usually be determined by measuring its voltage level. Generally, at least 80 percent nominal voltage on all three phases is considered a live bus, because that voltage level takes power system operating variations into account and works as a reasonable threshold. The decision to close the breaker into a dead bus is programmed into programmable protective relay (PPR) devices. The programmed rules that PPRs follow are known as arbitration rules.

In the simple microgrid in Fig. 1, the two breakers associated with the genset and IBR are in similar situations. When the microgrid bus is energized, the closing of these breakers requires a minimum angular and magnitude difference between themselves and the utility source on the other side of an open breaker. It is also possible that the following conditions exist for either breaker:

- A dead microgrid bus and a live source. This implies a "black start" in which the source is going to provide the voltage and frequency reference.
- A live microgrid bus and a dead source. PPR programming must not allow the closing of the breaker for a synchronous generator. PPR programming may allow closing into an IBR, because the IBR can begin commutation by phase-locking to the voltage.
- A dead microgrid bus and a dead source. This condition may allow breaker closing during commissioning activities.

II. GENERATOR SYNCHRONIZING

A textbook generator synchronization is illustrated in Fig. 2. A generator frequency is controlled by the prime mover and usually a valve that regulates the flow of fuel (or other flow, such as water for hydroelectric generators). The voltage magnitude (|V|) at the terminals of the generator is determined by the control of the field current (If).

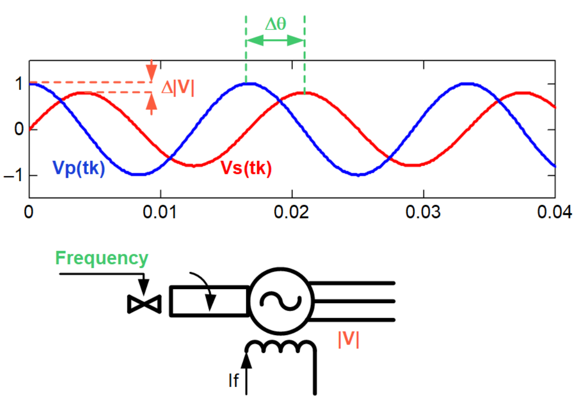

Fig. 2 Synchronizing a Genset

Fig. 2 also illustrates the waveforms of the voltages on each side of the breaker from the microgrid bus and the source terminals. The angular difference across the breaker terminals is $\Delta\theta$, and the magnitude difference of the measured voltages on both sides of the breaker is ΔV. When synchronizing (closing the breaker) to the utility, both differences must be within acceptable upper and lower limits.

Synchronization was historically done manually using a synchroscope or a light bulb [3]; today, PPRs are the dominant automatic synchronizers used. The algorithms implemented in PPRs are used to control the frequency and voltage magnitude through pulses (pulsing up or pulsing down) or analog bias set points. The PPR synchronizer adjusts the frequency and voltage magnitude of the source to be within acceptable limits with respect to the microgrid bus.

A different relay function (than the automatic synchronizer), the synchronism-check function (Function 25), is an independent permissive function to close the breaker. This function verifies that the phase angle and voltage magnitude difference is within acceptable limits. This permissive function is completely independent from the way that the generator is synchronized; whether that is accomplished with a synchronizer function or manual control.

A. *Function 25 in a PPR*

American National Standards Institute Function Code 25 verifies that a breaker can be closed by working as a permissive function in the breaker-closing schemes for PCC breaker and source breaker synchronization.

As shown in Fig. 3, Function 25 takes a reference voltage (Vp) that is used as the polarizing voltage on one side of the breaker and a synchronizing scheme (Vs) from the other side of the breaker. The function checks the angular difference and the voltage magnitude difference. If these are within limits, it issues a permissive signal (a contact closure or a binary signal) that allows the closing of the breaker.

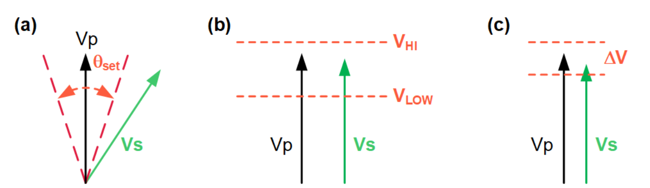

Fig. 3 Function 25 Checks

Implementations of Function 25 perform the following checks (as shown in Fig. 3):

- An angular difference check, in which the Vp and Vs angular difference is compared to a set angular difference ($\Delta\theta$set). This check is effectively an angular window.
- A voltage magnitude health check, in which the magnitudes of both Vp and Vs are compared to maximum (V_{HI}) and minimum (V_{LOW}) thresholds. If both are within the thresholds, the check is satisfied.
- An amplitude difference (ΔV) check, which ensures that the difference in amplitudes of the two voltage waveforms is less than a value (as shown in Fig. 3c).
- A slip check, in which slip, the difference in frequency of the two voltages, must be less than a threshold.

If the slip is small (slip < Smin, and Smin = 0.005 Hz, typically) the angle check considers static measurements.

If the slip is large enough (slip > Smin) then the measurements are considered dynamic, and it is possible to estimate a closing instant if the close time of the breaker is known.

Fig. 4 illustrates a condition in which Vs is rotating towards Vp at a certain rate, slip. Using (1), it is possible to calculate a compensated synchronizing voltage, Vsc. When the angular difference between Vp and Vsc is zero, it is the ideal time to issue a close command to the breaker. When the breaker contacts close, the angular difference between Vp and Vs is zero.

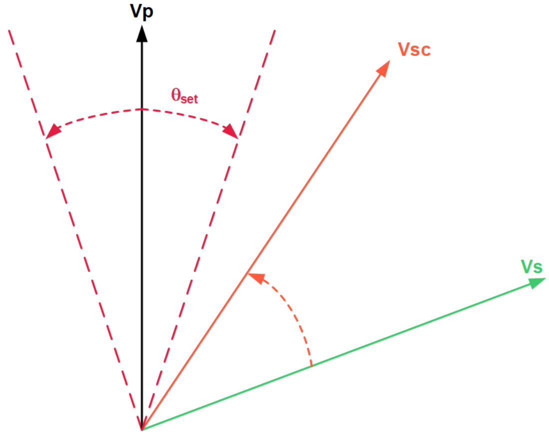

Fig. 4 Angular Check With Slip > Smin and Compensated Synchronizing Vector

$$\text{Ang}(\text{Vsc}) = \text{Ang}(\text{Vs}) + 360° \left(\frac{\text{slip}}{\text{fnom}} \right) \bullet \left[\frac{\text{Tcl(cyc)}}{\text{slip cycle}} \right] \quad (1)$$

where:

slip is the difference of frequencies between Vp and Vs.

fnom is the nominal operating frequency.

Tcl is the breaker closing time in cycles.

Vsc is the compensated voltage.

θset is the angular window allowed for closing the breaker.

B. Synchronizing Schemes of a Microgrid PCC

While for a single source there is a clear control scheme to manage the angular and voltage magnitude difference across a source breaker, the situation is more complex for a microgrid PCC breaker. In a microgrid, usually a system controller (also known as a microgrid controller [MC]) is in charge of dispatching the microgrid sources. Moreover, in the PCC location, an adjacent PPR is provided with synchronizing capabilities and sends raise and lower pulses to the sources. In modern microgrids, manual synchronizing is also still a possibility, in which the control of the sources is done locally using the pushbuttons of the source controller. For the three possible situations in a microgrid that are described here, the synchronizing schemes are named A25A, A25 and 25 [4].

1) Microgrid Synchronizing Scheme A25A

Fig. 5 shows the A25A scheme, in which the dispatching of the source(s) in the microgrid is done through the MC. The PCC PPR includes the sync-check and the dead bus arbitration logic to close the breaker. The raise and lower pulses originate in the MC based on the measurements provided by the PCC PPR.

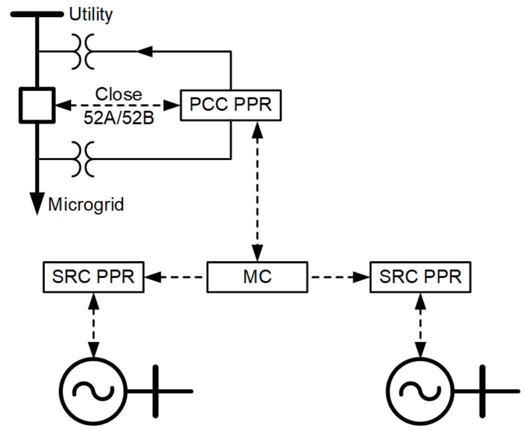

Fig. 5 A25A Scheme, MC Present

The MC is a flexible controller that can be programmed to use sources efficiently and control many at the same time with great flexibility. For example, while dispatching the sources for Function 25 on the PCC, an MC can simultaneously achieve a particular dispatch objective, such as equal load sharing or battery charging.

2) Microgrid Synchronizing Scheme A25

The A25 scheme, shown in Fig. 6, is simpler than the A25A scheme. If the MC fails or is under maintenance, synchronization needs to take place without an MC involved. The PCC PPR has synchronizer capabilities and is able to send raise and lower signals to the source PPRs through the network. The advantage to this scheme is its simplicity and reliability; the disadvantage is that other MC dispatch objectives cannot be met at the same time as synchronization. The A25 scheme is, for all intents and purposes, the backup scheme to the A25A scheme.

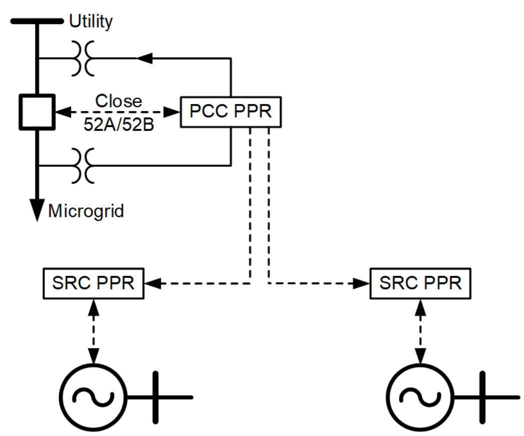

Fig. 6 A25 Scheme, MC Not Present

3) Microgrid Synchronizing Scheme 25

The 25 scheme, shown in Fig. 7, is the manual synchronizing scheme with an automated PCC 25 sync-check. This is the simplest of all three schemes. Through the front panel of a source PPR, a user modifies the frequency/power and voltage/VAR set points. Simultaneous to this, the user initiates a PCC 25 close logic; this logic stays active and closes the PCC breaker autonomously while the source PPRs are being manually dispatched. There are usually two individuals communicating over radio for this scheme; the person at the PCC advises the slip and voltage differences, while the person at the source PPR dispatches the source(s) from the PPR front panel.

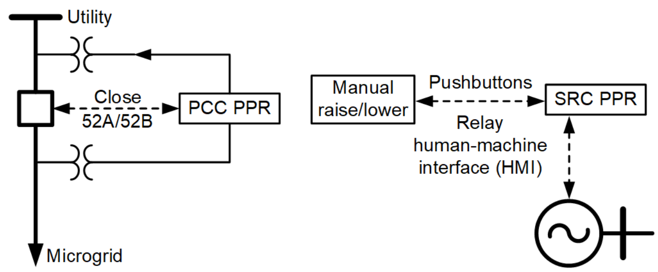

Fig. 7 25 Scheme, No Communications Available (No MC)

C. Synchronizing Function Discussion Points

Function 25 compares the angular and voltage magnitude differences across the breaker. The voltages used at both sides of the breaker are usually single-phase voltages that are either of the same nature (phase-to-ground or phase-to-phase) or adjusted in magnitude and angle (for example, VA compared to VAB). The Vp voltage is usually selected from a three-phase measurement (the three-phase measurements are present for other purposes as well). However, Vs is a single-phase input.

1) Three-Phase Comparison

In lower-voltage systems, such as microgrids, it is common to have a single-phase fuse blown or one or more recloser poles stuck open. It is also common to have a broken (open) conductor. A phasing change can also happen inadvertently after maintenance. With single-phase comparison, the above conditions do not signal a problem to the sync-check Function 25. Therefore, implementing the sync-check using three-phase measurements on both sides provides the greatest security for microgrids. The check does not need to be performed for each phase; however, the phase sequence must be verified and any presence of negative-sequence voltage (also known as "negative sequence" or "unbalance") is used to block the breaker from closing.

2) Failed Potential Transformer (PT)

A failed PT on either side of the breaker takes Vs or Vp to a zero (low) measurement. A failed PT must prevent Function 25 from closing.

III. CLOSING INTO A DEAD BUS

Closing a DER breaker to a microgrid or the microgrid to the main grid (through the PCC breaker) should normally be performed with a sync-check (Function A25A, A25, or 25) scheme described above, which assumes healthy voltages (Vp and Vs) on both sides of the breaker, as shown in Fig. 8. This section describes some circumstances in which there is a dead bus (low-voltage measurement) on one or more sides of a breaker and closing a breaker is desired.

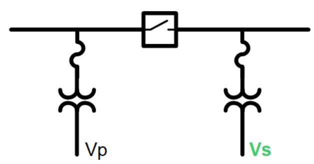

Fig. 8 Voltage Measurements Across a Breaker

For example, to declare a dead bus measurement, a voltage measurement below 20 percent of nominal voltage is typically used. If Vp < 20 percent nominal, the DER side (or microgrid side) bus is declared dead. If Vs < 20 percent of nominal, the microgrid bus (or utility) is declared dead. If the voltages are above the threshold (80 percent), they are said to be live.

A. DER Breaker Closing Onto a Dead Bus

Table I shows the possible states of the two voltages measured on both sides of the source breaker. A source breaker may be allowed to close to a dead microgrid bus. This can happen if the microgrid requires the particular DER to black start the microgrid. During commissioning of the DER and microgrid, this condition can happen, and the breaker may be allowed to close to a dead microgrid bus.

TABLE I
DER BREAKER CLOSING CONDITIONS

Source	Microgrid Bus	Comments
Dead	Dead	Commissioning activities
Dead	Live	Never allow closing for a synchronous generator; may allow closing for an IBR
Live	Dead	May allow closing for black start or commissioning
Live	Live	Use 25 sync-check permissive

Allowing the closing of the DER breaker when both sides are dead might be required during commissioning activities and allowed only during that time. It can sometimes be used when having battery IBRs as black-start sources; however, this requires a greatly oversized (expensive) IBR.

For most sources, closing a live bus to a dead source bus is not good, because that can damage the source. However, an IBR source might require voltage to start commutation; this scenario is allowed.

B. IBR Dead Bus Considerations

Most inverters can synchronize to a live bus without the aid of traditional A25A strategies using a breaker. When the IBR's alternating current side is energized from the microgrid bus, and a command is given to begin commutation (power flow), the power electronics sense the bus voltage magnitude and frequency from its voltage measurements, and match those parameters on commutation commencement. Even though the IBR might not be commutating, it is generally desirable to have the ac side of the IBR remain energized. This is to maintain the electronics in a ready state, temperature condition the batteries (heat or cool), or provide communications to other systems without draining the batteries, and is commonly known as shore power.

When an IBR is not commutating and the ac bus is dead (for example, during a black start), commanding the IBR to begin commutation requires that the IBR can energize the load without being overloaded, which is sometimes referred to as cold load pickup. Most IBRs begin commutation at a voltage at or near zero and ramp to nominal in a few seconds; this limits transformer inrush and cold load pickup problems that commonly plague IBRs. However, ramping voltage of a dead microgrid bus with connected loads that have not been isolated is not optimal for many reasons, including chattering of control contactors, sensitive electronics, and more.

Fig. 9 illustrates a BESS IBR energizing a dead bus with connected loads. In this example, the IBR was connected to a load bank. The load bank was preset to a predetermined load. The load bank has a cooling fan with an airflow-providing switch interlock that must be made before the load contactors close to apply the load.

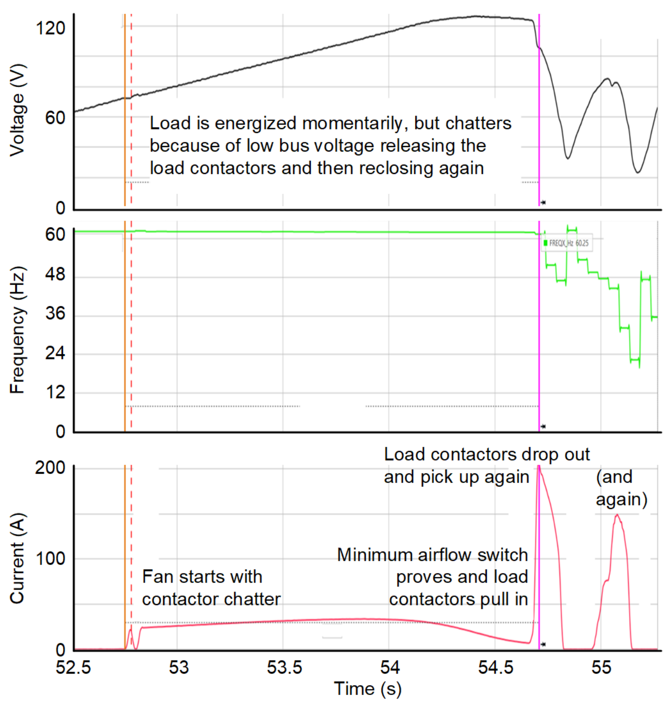

Fig. 9 IBR Inability to Energize a Dead Bus With Connected Loads

The following can be observed in Fig. 9:

- The IBR is ramping the voltage (top black trace). This is done to avoid inrush and prevent IBR overloads associated with a full voltage turn-on.
- The vertical dashed line indicates the moment when the cooling fan starts. It is at a bus voltage of around 70 volts (the fan is contactor-controlled).
- The bottom trace is phase current. At the moment that the fan starts, the current is observed with a momentary dropout (chatter) because the IBR has pulled back on the voltage ramp (this is difficult to see on the scale of the figure).
- With the fan momentarily disconnected, the IBR continues to ramp the voltage, and once again the fan contactor pulls in. Because the fan was already spinning from the previous attempted start, the voltage pullback is low enough that the fan contactor remains closed.
- As the fan approaches operational speed (typical fan motor start curve where the current rolls off), the airflow switch interlock operates and the load contactors pull in, applying the load to the bus.
- The large, suddenly-applied load causes the IBR to significantly pull the bus voltage back to the point where the load contactors drop out.
- With the load contactors dropped out, the IBR continues to ramp the voltage from the pullback point and the cycle continues, sometimes indefinitely.

In this example, the applied load was about half of the IBR nameplate rating.

A simple enhancement to improve the performance of the IBR during dead bus energization is to add an electrically operated breaker between the IBR ac bus and the microgrid bus, and also control the startup sequence with a PPR, as shown in Fig. 10.

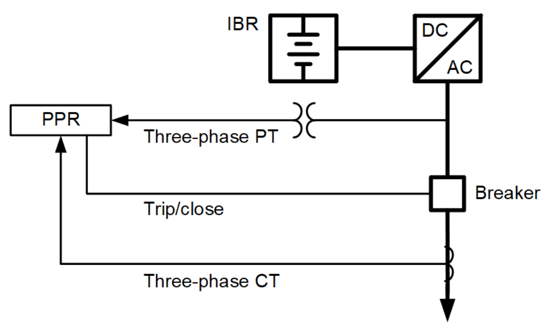

Fig. 10 IBR Addition of Electrically Operated Breaker

The new breaker is now controlled by the PPR that monitors the IBR commutation commands and the IBR bus voltage to determine when the ramp is complete. Once the ramp is complete, the PPR issues a breaker close command. The final close command is further conditioned with a 25 (synchronization) element and dead bus permissive, as there are several seconds between the IBR commutation start command and the ramp completion in which the microgrid bus might become energized by another DER or even a utility.

With the PPR controlled start and the same configuration as in Fig. 9, the following performance was observed in Fig. 11.

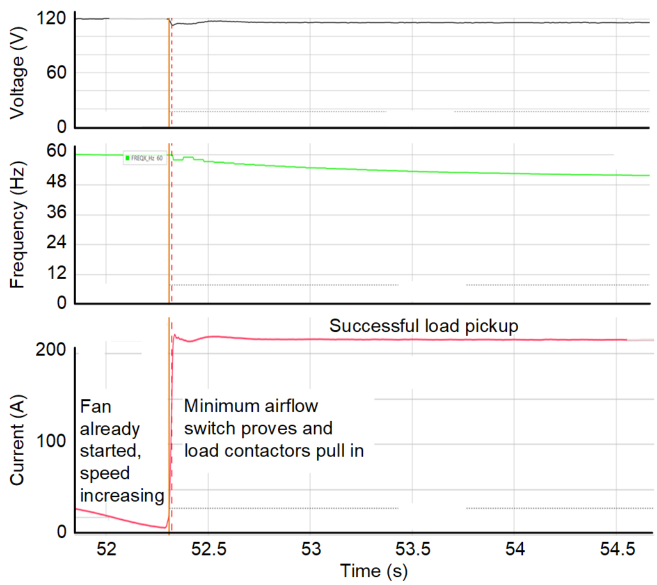

Fig. 11 IBR Ability to Energize a Dead Bus With Connected Loads After Addition of Breaker

The following improvements can be observed in Fig. 11:

- The breaker closes after the IBR ramps to nominal voltage. The data for this are to the left of the plot (not shown, as the total duration of the captured data rolled off).
- The bus voltage of the IBR is at nominal when the breaker is closed—the microgrid bus is not subjected to a ramping voltage.
- At the left of the plot, the cooling fan approaches operating speed. At operating speed, the airflow proving switch interlock makes and closes the load contactors.
- The load is applied at the vertical dashed line. The load is stable and no bus voltage pullback or load chatter is observed.
- The frequency dropping is because the IBR is in grid-forming mode with droop.

C. Microgrid PCC Breaker Closing Into a Dead Bus

Table II illustrates the possible states of the voltages on both sides of the PCC breaker. Having both the utility and microgrid bus dead is applicable when there are commissioning activities on the site. It may be necessary to exercise the breaker and test; therefore, logic in the PPR is commonly enabled for this during test mode only. The situation when both are live is the normal situation and requires the sync-check functionality and one of the synchronizing schemes described above.

It is acceptable in most cases to enable the PCC breaker to close when the microgrid is dead and the utility is live; this implies that the microgrid load will be satisfied from the utility.

TABLE II
MICROGRID PCC BREAKER CLOSING CONDITIONS

Utility	Microgrid Bus	Comments
Dead	Dead	Commissioning activities
Dead	Live	May be allowed if backfeeding to the utility is acceptable
Live	Dead	May be allowed if loads can be served by the utility
Live	Live	Use 25 sync-check permissive

If backfeed from the microgrid to the utility is allowed, the condition where the utility is dead and the microgrid is live can allow closing of the breaker. This is done when a microgrid is required to backfeed a small community or an adjacent building through a medium-voltage utility distribution system.

D. Dead Bus Arbitration

The previous sections lead into the considerations needed for a dead bus. The logic and interlocks to close the breaker, including A25A, A25, and 25 logic, should be in the PPR that has control of the breaker. The PPR provides the adequate protective relaying schemes to open the breaker, and, in a microgrid, it is also responsible for verifying and ensuring that the conditions needed are met to close the breaker.

Fig. 12 shows an example front panel of a PPR controlling a microgrid PCC breaker.

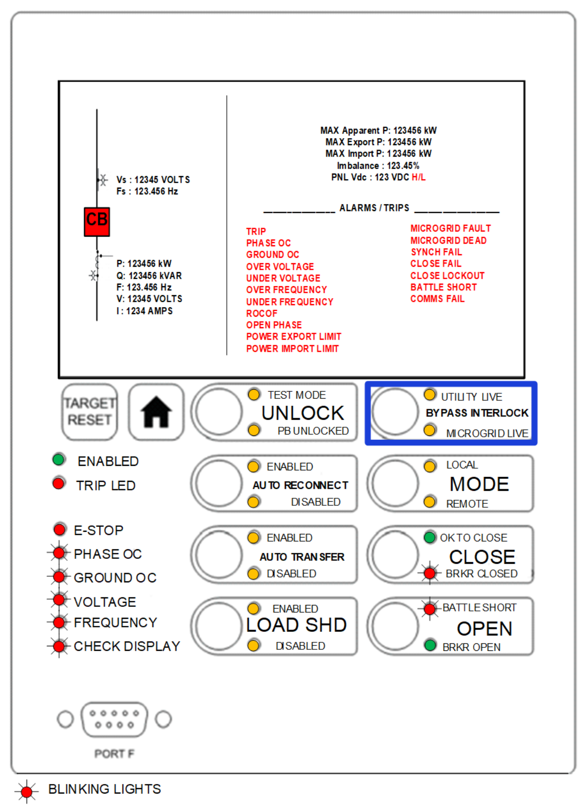

Fig. 12 PPR That Controls Breaker

The device provides the required Function 25 to allow the breaker to close when the utility and the microgrid are both live. A pushbutton in Fig. 12 is highlighted; this button gives the user the ability to allow breaker closing when the utility side is dead and the microgrid side is live. The condition of live utility, dead microgrid, and A25A, A25, and 25 protection is normal operation and does not require any special authorization.

For security, many implementations of dead bus arbitration force the control of the breaker to be LOCAL only, not allowing a REMOTE closing of the breaker through an HMI. There is an built-in message to the operator to make sure that there is a dead bus before closing the breaker. The "bypass interlock" button in the HMI enables the closing of the breaker to a dead bus, allowed by the logic programmed in the HMI of the PPR. This HMI, however, needs to be unlocked for the control buttons to become active.

There are also other options that users may program in a PPR; the above is one example that illustrates the care needed before closing the breaker into a dead bus.

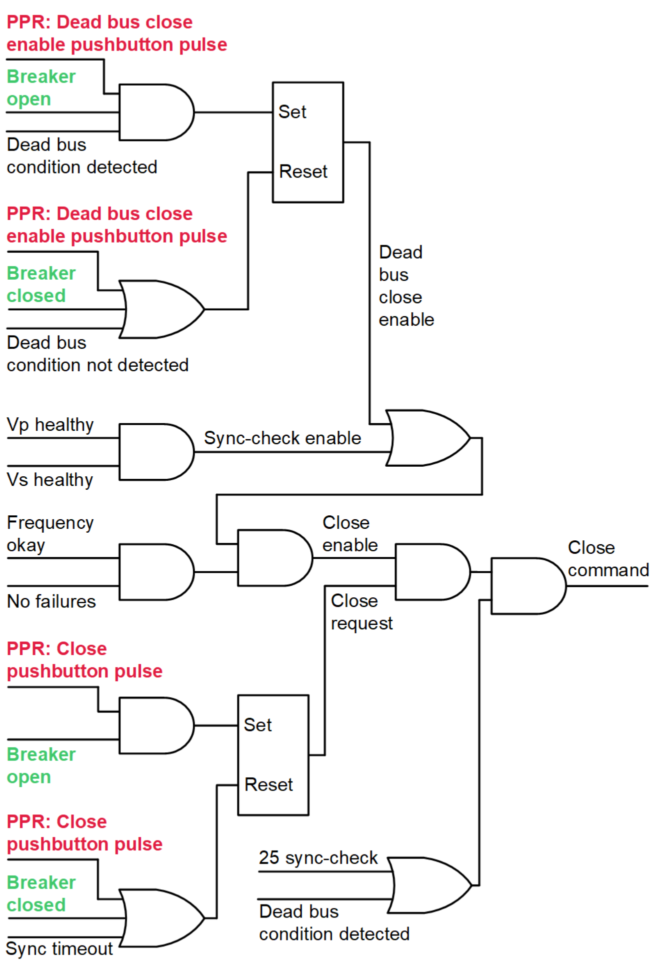

Fig. 13 PPR Dead Bus Arbitration Logic

A simplified implementation of dead bus arbitration logic is shown in Fig. 13. The logic internally implements Table I or Table II permissions and creates a signal called "dead bus condition detected" that asserts for the selected condition in the table. When the breaker is open, the dead bus close enable pushbutton needs to be pushed ("bypass interlock" in Fig. 12) to set the permissive function. When the breaker closes, the same button is pushed again, or a dead bus condition is detected, the latch resets.

The PPR CLOSE pushbutton starts the close requests that would start a timer (not shown in Fig. 13) and enable the path for closing the breaker. This request is reset when the breaker closes or the time window allocated for the closing has timed out. The enable and request signals wait for either the sync-check (if the two voltages on both sides of the breaker are healthy) or if the dead bus condition has been detected. The close command is routed to the output contact of the PPR.

E. Considerations and Discussion

The importance of dead bus arbitration logic in microgrids should not be minimized. It has important implications in the operation of a microgrid and its sources.

1) Failed PT

A failure in the measurements on either side of the breaker can provide the wrong information to the protective relay.

In Fig. 14, two possible voltage transformer (VT) installations are illustrated. PT-1 is provided with fuses in each phase for the protection of the VT. PT-2 is protected with a miniature circuit breaker (MCB), that has its three poles gang-operated and provides a dry contact that follows the position of the poles. Fuse blocks with blown-fuse-detection circuits can also be added. The PPR blocks all breaker closing when either a MCB or fuse is open.

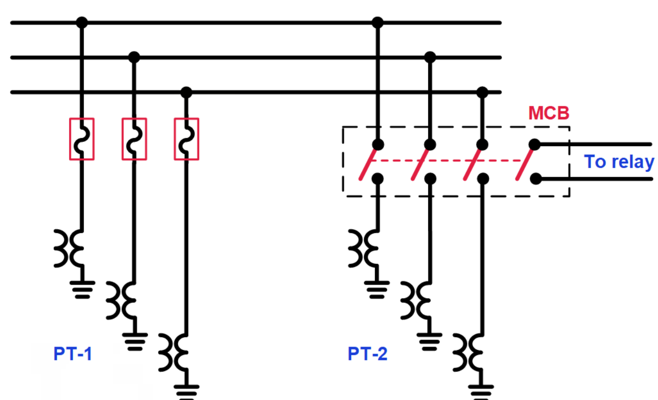

Fig. 14 Fuse (PT-1) and MCB (PT-2) Wired Voltage Transformers

For conditions such as open conductors or failures in the PT circuit that do not appear on an MCB or fuse indicator, most PPRs include dedicated logic to detect failure in the VT circuit. This logic is known as loss of potential (LOP) logic, and it is generally based on the fact that for a VT failure, the voltages change and the currents do not. For LOP logic to supervise Function 25 and the dead bus arbitration logic, the following must be considered:

- LOP is used for three-phase measurements. It is not applicable to single-phase measurements.
- LOP uses current measurements to detect a VT failure. The logic monitors for a change in voltage and no change in current. Other implementations monitor for unbalance in the voltages (v2 or v0) and no unbalance in the currents (no I2 and no I0). There is a dependency on the current measurement, and for very low current flows (or no load), LOP might not be able to detect a failure.

A simple example of LOP logic is shown in Fig. 15. The PPR is monitoring a sudden change in the measured voltages (ΔV) and the absence of a change in the measured currents (ΔI). That sets the LOP logic bit and can be used for disabling critical voltage functions and alarm functions. When the voltage is determined to be healthy, the logic resets. The logic in Fig. 15 is simplified with respect to the actual implementation in the PPR.

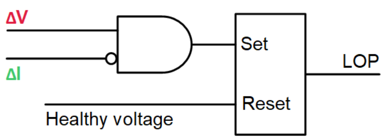

Fig. 15 PPR Dead Bus Arbitration Logic

2) Out-Of-Phase Synchronization (OOPS) Logic

Closing the breaker of a source that is 180 degrees out of phase has been reported, and is certainly a possibility in microgrids [1]. The consequences can be extremely damaging to sources.

The large angle difference when closing for these events forces very large currents in generators, cables, breakers, and switchgear. Currents can be well above 5 per unit (pu). To provide inrush current support for transformer energization on a dead bus and also provide supervision of closing into an energized bus, a simple OOPS protection scheme can be used as a means to protect the generator. Fig. 16 illustrates the concept.

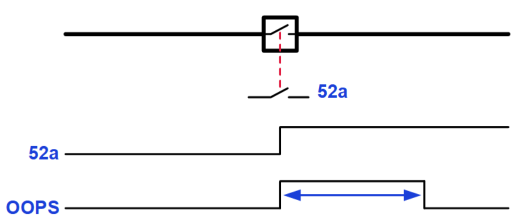

Fig. 16 OOPS Time Window

Upon closing into a live bus, when the generator is correctly synchronized to the bus, the current at the time of breaker closing should be near zero. The OOPS scheme uses a relatively low-set 50 element and is enabled upon closing the breaker for 15 to 20 cycles. Once the time window has elapsed, the low-set 50 element is disabled to allow for the normal protection scheme to be active. If there is a dead bus, the OOPS scheme does not enable, thereby allowing full generator capability to energize transformers and other loads. OOPS logic is very similar to switch-onto-fault (SOTF) logic employed in PPRs in distribution circuits [5].

IV. CONCLUSIONS

PPRs must be used at every PCC and DER breaker location. These PPRs contain logic for A25A, A25, 25, dead bus arbitration, IBR black-start logic, PCC backfeed bypass LOP, and OOPS protection. Dead bus arbitration must consider failed PTs, commissioning needs, and more. The authors prefer to use both MCBs with gang-operated poles and an output contact in tandem with LOP logic in a relay to detect PT failures.

V. REFERENCES

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VI. VITAE

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