Asymmetric Grounding of Auxiliary DC System at Large Substations.

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I. Introduction

The availability of DC auxiliary system is critical for reliable operation of power equipment. The DC auxiliary system shall:

a) support required operation (closing/tripping) of power equipment for normal and emergency conditions, i.e. guarantee required operation when power device called to operate.

a) do not operate falsely, i.e. not operate when device did not call for operation.

Traditionally DC auxiliary systems were designed as ungrounded in order not to be affected by the singular fault to ground at any system bus. Special fault detection devices were added for detection of this singular fault to prevent shut down of DC system after development of the second fault at the opposite bus.
Substations using a conventional ‘symmetrically grounded mode of DC system and having a large capacitance to ground from the DC system are known to be vulnerable to false operation of relay protection as a result of an unintended DC ground [1,2].

II. Performance of Symmetrically Grounded DC System under Fault to Ground Condition.

This phenomenon of false operation may be make clear by using simplified scheme of DC system, presented at Fig. 1.

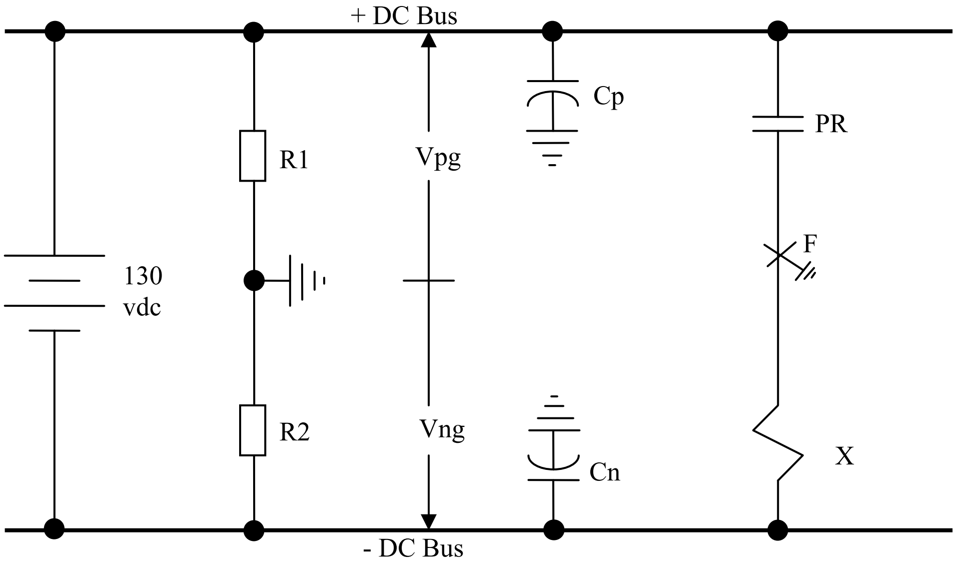

Fig 1 - Symmetrically Grounded System

Equal value resistors R1 and R2 (typically 10,000 ohms each) divide the battery voltage so that Vpg is normally about +65 vdc and Vng about -65 vdc for a 130 volt system. Capacitances Cp and Cn represent the total capacitance to ground of surge suppression devices in DC powered equipment plus the distributed capacitance of the station DC wiring. In distribution substations, this capacitance is typically a few of microfarads, but may reach several hundred microfarads in large transmission substations. Since these capacitances are effectively in parallel with R1 and R2, Cp is normally charged to +65v and Cn is charged to -65v.

Device X represents a circuit breaker trip coil or auxiliary relay coil, initiated by protective relay contact PR. Point F is a potential ground fault location on the initiating lead to device X. The voltage to ground at F, prior to a fault, is -65v. When a fault to ground occurs at F, coil X becomes connected in parallel with R2 and Cn. Since the resistance of coil X is much less than the resistance of R1, Vng falls to almost zero volts and Vpg increases to full battery voltage. This change of state entails a redistribution of charge on Cp and Cn, i.e. Cn is discharged and the charge on Cp increases to conform to its new, higher applied voltage. The transient discharge current of Cn and the charging inrush to Cp both flow through the fault and coil X, tending to cause a momentary unwanted operation of device X, e.g. a false trip of a circuit breaker or auxiliary relay. The more values of the capacitances Cp and Cn, the more energy is delivered to device X. Field experience and laboratory testing have both show that unwanted tripping can occur with values of capacitance found in large substations.

III. Performance of Asymmetrically Grounded DC System under Fault to Ground Condition.

Figure 2 shows an asymmetrically grounded system. Resistor R3 is added so as to skew the normal voltages to ground. In the asymmetrical DC system, Vpg is normally about 115v and Vng is about -15v. The R_{PF} is resistance of fault between positive pole and ground, that shall be detected and evaluated.

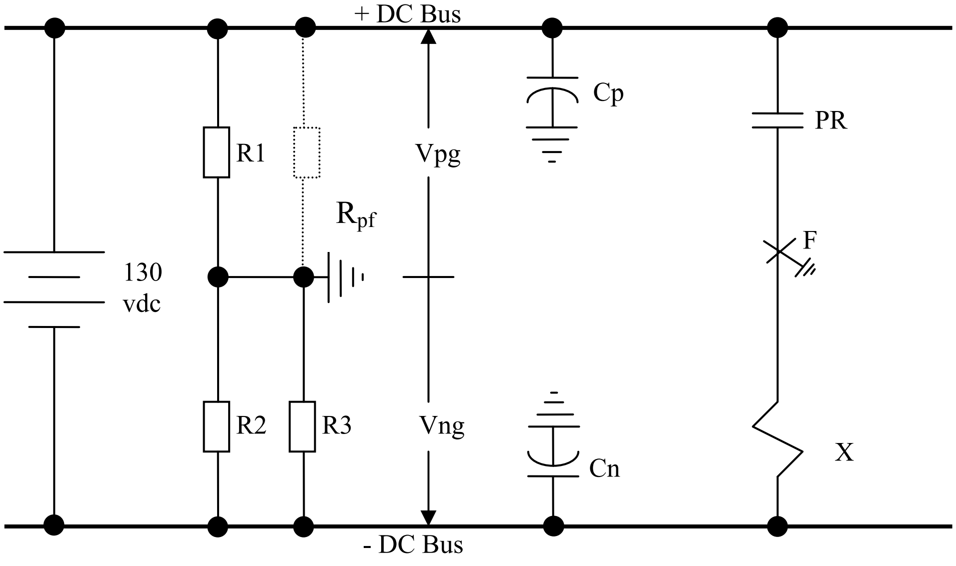

Fig 2 - Asymmetrically Grounded System

With the asymmetrical voltage distribution, the changes in charge levels on Cp and Cn caused by a fault at F are much less than those in a symmetrically grounded system. Laboratory testing has shown that, with the most vulnerable auxiliary relays and the maximum practical amounts of expected capacitance, pre-fault magnitudes of Vng less than 26 volts will not cause unwanted operations of the auxiliary relays. The 15 volt design value of Vng for the Asymmetric DC Grounding system provides a margin below that 26 volt threshold.[1]

IV. F Fault Detection and Evaluation Scheme for Asymmetrically Grounded DC System.

The DC ground fault detector for Asymmetrical DC grounding is implemented by means of calculations in a Momentum Programmable Logic Controller (PLC). The PLC measures scaled-down values of the DC pole voltages Vpg and Vng and evaluates (calculates the value of any DC system single fault resistance), that causes the ratio Vpg/Vng to deviate from the ratio determined by the known values of R1, R2, and R3 (see Fig. 3).

For Vpg , Vng , and R_{1F} will have:

$$V_{PG} = V_{DC} \frac{R_{1F}}{(R_{1F} + R_{23})} \qquad (1)$$

$$V_{NG} = -V_{DC} \frac{R_{23}}{(R_{1F} + R_{23})} \qquad (2)$$

$$R_{1F} = \frac{R_1 R_{PF}}{(R_1 + R_{PF})} \qquad (3)$$

Here

V_{DC} is DC battery voltage
R_{1F} is resistance of parallel connected R1 and R_{PF}.
R_{23} is resistance of parallel connected R2 and R3.

Dividing (1) by (2) will give:

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[1] Faults to ground on the positive DC bus cause Vn to increase and make the system again vulnerable to false tripping if an accidental ground fault should occur on an initiating lead. The design of the asymmetric scheme and its ground fault detector is to produce an alarm for positive-pole ground faults of 10,000 ohms or less, the fault resistance threshold at which Vng is more than 26 volts.

$$R_{1F} = -R_{23}\frac{V_{PG}}{V_{NG}} \qquad (4)$$

By excluding R_{1F} from equations (3) and (4) for evaluated value of resistance from positive pole to ground R_{PF} will have:

$$R_{PF} = -\frac{V_{PG}R_{23}R_1}{V_{PG}R_{23} + V_{NG}R_1} \qquad (5)$$

Dividing nominator and denominator of expression (5) by $R_{23}R_1$ will receive:

$$R_{PF} = -\frac{V_{PG}}{V_{PG}G_1 + V_{NG}G_2} \qquad (6)$$

where

G_1 is the conductance of resistor R1, i.e. G_1 = 1/R1; and
G_2 is the conductance of the parallel connection of R2 and R3, i.e. G_2 = 1/R2 + 1/R3.

By performing similar manipulations for the negative pole to ground resistance R_{NF} will have:

$$R_{NF} = -\frac{V_{NG}}{V_{PG}G_1 + V_{NG}G_2} \qquad (7)$$

It is important to underline that expressions (6) and (7) will provide accurate results only if conductances G1 and G2 match the real physical values of conductances for DC scheme. It requires preliminary calibration of fault detection and evaluation scheme.

V. Calibration of Fault Detection and Evaluation Scheme for Asymmetrically DC System.

The DC ground detector algorithm includes a manually armed automatic calibration procedure to accurately calibrate the fault resistance calculation by nulling out normal tolerance variations in the values of grounding resistors R1, R2, and R3. Goal of calibration process to create in PLC memory virtual values of $R1_{PLC}$, $R2_{PLC}$, and $R3_{PLC}$ that are mirrors real physical values R1, R2, and R3. The automatic calibration can also be used, if desired, to null out normal leakage resistance in the station DC system.

Process of calibration consists from two Calibration Routines G1 and G2. In the beginning of process Calibration Routines G1 and G22 adjust values of resistors $R1_{PLC}$ and $R2_{PLC}$ to match real values of these resistors in balanced scheme (resistor R3 is disconnected). Then resistor R3 is manually connected in parallel to resistor R2, and

Routine G2 is used to match value of parallel connection of resistors R2 $_{\text{PLC}}$ and R3 $_{\text{PLC}}$, saved in PLC memory, to real value of these resistors' combination.

By assuming that R1 $_{\text{PLC}}$=R2 $_{\text{PLC}}$=10 kΩ and using the real measured values of voltages Vpg and Vng, the following value of D is calculated:

$$D = -V_{PG}G0 - V_{NG}G0 \qquad (8)$$

where

$$G0 = \frac{1}{R1_{PLC}} = \frac{1}{R2_{PLC}}$$

If in real scheme R1=R2, $|V_{PG}| = |V_{NG}|$, value of D in formula (8) is equal to zero, and no calibration is required.

Calibration Routine G1 is activated if $|V_{PG}| < |V_{NG}|$, while Calibration Routine G2 is implemented for $|V_{PG}| > |V_{NG}|$ condition.

A. Calibration Routine G1

If absolute value of voltage V_{NG} is higher than absolute value of V_{PG} the value of D in formula (8) is positive. It may happen if in real scheme R1 < R2.

To match real scheme the value of R1 $_{\text{PLC}}$ in PLC memory shall be reduced, i.e. G1 shall be increased. In order make value defined by formula (8) equal zero, which indicates balanced conditions, conductance from positive pole to ground shall be increased by adding some value G. This value may be found by solving the following equation

$$-V_{PG}(\ G0 + G\ ) - V_{NG}G0 = D - V_{PG}G = 0 \qquad (9)$$

From here for G

$$G = \frac{D}{V_{PG}} \qquad (10)$$

As a result of this adjustment virtual conductance G0, associated with real resistor R2, remains unchanged and equal original value 0.1 mS. For virtual conductance G1, associated with real resistor R1, will have:

$$G1 = G0 + \frac{D}{V_{PG}} \qquad (11)$$

Between virtual values G0 and G1, residing in PLC memory, the following relationship exists:

$$\frac{G0}{G1} = \frac{R1}{R2} \qquad (12)$$

B. Calibration Routine G2

By manually closing calibration switch TS-1 (switches TS-2 and TS-3 are opened-see Fig. 3) program is directed to adjust R2 $_{PLC}$ value. At this stage of calibration procedure the corrected value of G1, defined by formula (11) and original value of G2=G0 are used to calculate

$$D = -V_{PG}G1 - V_{NG}G0 \qquad (13)$$

If this value of D is positive, no correction of G2 is required. Otherwise the corrected values of G2 and R2 $_{PLC}$ are calculated by using the following expression:

$$G = \frac{D}{V_{NG}} \qquad (14)$$

$$G2 = G + G0 \qquad (15)$$

$$R2_{PLC} = \frac{1}{G + G0} \qquad (16)$$

By closing switch TS-2 the resistor R3 is connected in parallel to resistor R2, which sharply reduce absolute value of V_{NG} and make value of D negative. Now value of D is recalculated by using expressions (13-16).

Closing switch TS-3 terminates calibration process and makes system ready for normal operation.

VI. Implementation of Asymmetrically Grounded DC System.

Asymmetrical DC ground system used in laboratory testing is shown at Fig. 3. It includes Momentum PLC, which analog inputs are connected to DC Grounding scheme thru dividing resistors. Three manually operated switches TS-1, TS-2, and TS-3 are used in calibration process. Physical outputs on the PLC operate external alarm relays and for positive and negative ground faults, respectively. Contacts from these relays can be used for local annunciator and/or RTU indications as needed. The PLC requires a power supply voltage of 24 vdc for its operation. This voltage is provided by a DC/DC converter (PS) powered from the main substation battery.

The above mentioned Momentum PLC is part of substation Local Area Network (LAN), which includes Human Machine Interface (HMI). The HMI provides local information about status of DC system to substation operator, as far as reports information to system dispatcher thru SCADA system.

The calculated fault resistance value is displayed at HMI screen, when its magnitude is less than 100 kΩ. For fault resistances less than 10 kΩ, the local/remote alarms are activated in addition to the numerical display. The alarm indicates which pole, positive or negative, is faulted after the fault is detected for at least 5 seconds. For calculated fault resistances of more than 100 kΩ, the code “999” is displayed, indicating that the fault resistance is infinite or too high to be of concern.

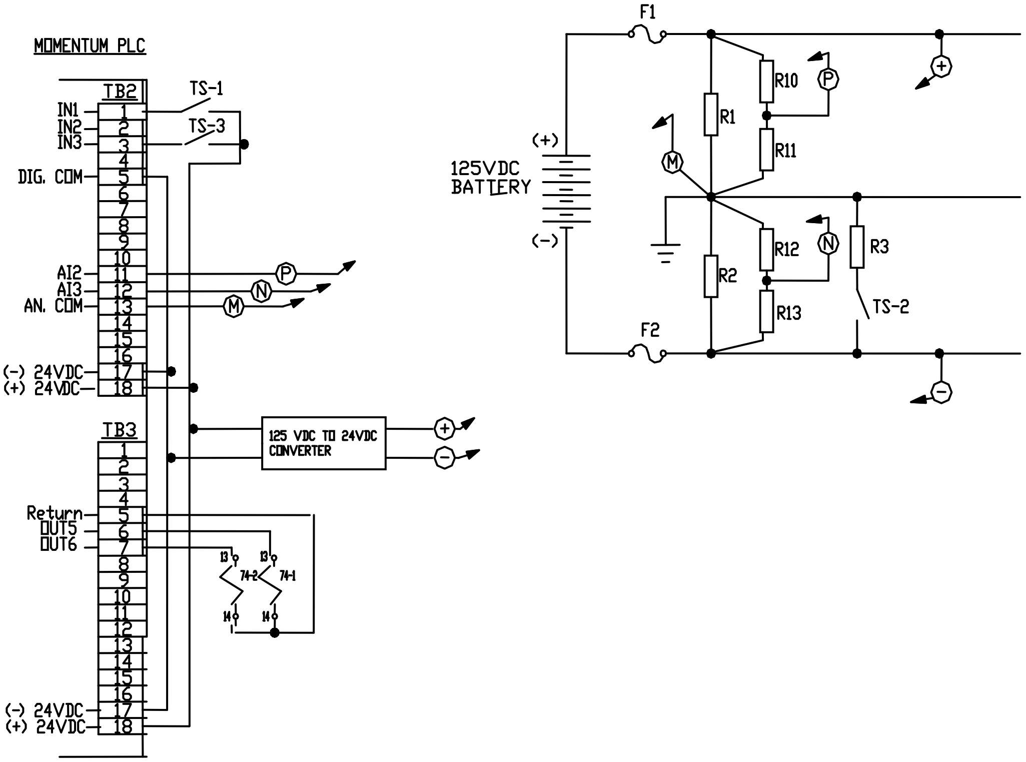

Fig. 3 Asymmetrical DC Ground Circuit Diagram

Momentum PLC program was developed and tested. Calculation of DC ground fault resistance and activation of fault alarms is implemented in a dedicated Modicon Momentum PLC which measures the pole-to-ground voltages of the DC system. In an automated station, the PLC is equipped with a ModBus Plus or Ethernet adapter for communication to the automation network.

The developed Asymmetrical DC Grounding system was successfully tested at substation. Functioning of the system was evaluated for asymmetric as well as for balanced DC grounding system configurations. In both conditions, the developed system successfully detected positive and negative grounds below 100 kΩ and generated separate alarms for positive and negative grounds below 10 k Ω

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The system test also included an HMI configured with a new template for this system to provide real time local information on positive and negative to ground resistance values. The HMI also displays separate alarms for positive and negative grounds when real time resistance values drop below 10 kohm at either positive or negative DC bus. The HMI also forwards these alarms to the Energy Management System.

VII. Conclusions.

1. Asymmetric Grounding of Auxiliary DC System permits avoid false operation of relay protection due the developing pole to ground faults at substations with large DC to ground capacitances while providing possibility in real time mode evaluate values of resistance to ground at both poles of battery.

2. Asymmetric DC Grounding system was developed and successfully tested at laboratory and substation. Functioning of developed system was evaluated for asymmetric as well as for balanced DC grounding systems. For both conditions, the system successfully detected and generated alarms for positive and negative grounds at the level of 10 kohm without intervention of substation operator.

3. HMI data base was modified to provide local information about real time resistances to ground below 100 kohm for both positive and negative DC buses. If real time resistances values drop below 10 kohm at any DC buses the HMI displayed alarm with indication of affected buses.

4. The locally and remotely available information from the DC system shall include positive and negative DC ground alarms, and also comprise analog information about positive and negative to ground resistances.

VIII. Acknowledgments

The authors gratefully acknowledge valuable comments, provided by David Gowhari, Terry Chapman, and Bill Corbell,

IX. References

[1] Jeff Roberts, Tony J. Lee ‘Measuring and Improving DC Control Circuits’, Proceedings of the 25th Annual Western Protective Relay Conference, Spokane, WA, October 1998 (available at http://www.selinc.com/techpprs.htm)

[2] Special Publication by the IEEE Power System Relaying Committee Relay Trip Circuit Design Working Group 'Relay Trip Circuit Design', April 1999, pp. 62-64

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