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Electrical safety requirements in DC distribution systems

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Abstract: This paper focuses on the safety requirements for the DC bus distribution systems up to 1500 VDC. High DC bus voltages are attractive for keeping the current and copper weight low. However, if the DC bus voltage exceeds 75 VDC, additional safety measures are required. Regulations require double protection measures. The first protection is mostly provided by proper electrical insulation. A second active protection system is also installed, this detects insulation failures and switches off the power supply. Often the residual current detector (RCD) is used which detects leakage current in earthed systems but is difficult to build for DC systems. Another active technique is to install a floating or unearthed system with an insulation resistance monitoring device (IMD). In this paper the advantages and disadvantages of both systems are compared. A simple IMD technique is presented together with fault simulations and EMC immunity test results. This paper also contains a brief review of additional safety requirements for DC distribution systems.

Keywords: safety, instrumentation, DC system.

1 Introduction

This paper focuses on the safety requirements for the DC bus distribution systems. They are used in many new electrical systems like photovoltaic (PV) installations[13], fuel cells, batteries, uninterruptible power supply (UPS) systems and electric vehicles(EV)[8]. High DC bus voltages are highly effective at keeping the current low and producing light weight electronics. However, if the DC bus voltage exceeds 75 VDC [6] additional safety measures are required[4, 6] in order to avoid the electrocution of users and maintenance personnel.

Regulations require double protection measures[11] against electrocution. The first protection is mostly provided by proper electrical insulation. The second protection measure is mostly provided by an active protection system that detects failures and automatic disconnects the supply voltage. A double electrical insulation is also allowed under certain conditions[4, 11] but unpractical and provides no fault information. In this paper two active protection systems [14] will be compared for DC bus distribution systems.

AC(50/60 Hz) systems are used for long periods. In these AC systems, the most common active protection system is the residual current detector (RCD) that detects leakage current in earthed systems.

Another active protection system is an insulation resistance monitoring device (IMD) that measures insulation resistance between conductor and earth in a floating system.

For installations in buildings both techniques are well defined in safety standards [9-12]. The building electrical safety standards are derived from [11] and are in Europe translated into national standards. According to these standards, several earthing systems can be installed for DC and AC distribution systems e.g. IT, TT or, TN wiring systems. For the residential distribution grid a TT system (fig. 2) is mostly used with an earthed neutral (N) conductor at the distribution transformer or power source. In this system, an active safety component with RCD can be installed. For application in a residential distribution grid the RCD protection is useful because it is able to locate and isolate the fault and the technology is easy. It is also possible to install an IT system (fig. 1) with lines L1, L2, L3 or N floating (not connected to earth). In these systems an active safety procedure with IMD can be installed. These IT systems are seldom used in AC distribution systems and more in DC distribution systems. Sometimes IT systems for AC distribution are used in hospitals or critical production environments [7].

The main scope of this paper is to present and compare IMD and RCD active protection systems for DC voltage distribution systems that exceed 75

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VDC and below 1500 VDC. Therefore a practical case of a PV system will be used. A simple IMD technique[15] for DC systems is also presented together with fault simulations and EMC immunity test results. Besides insulation faults the DC voltage distribution system needs to be protected against short circuit, over voltages and in some cases to lightning strikes, more information can be found in standards and literature [8,11].

Fig.1 Electrical grid with IT earthing

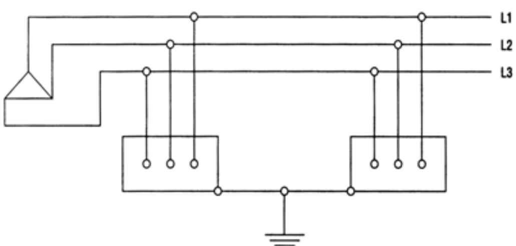
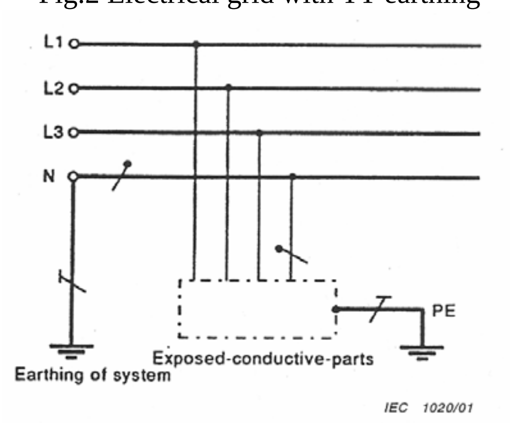


Fig.2 Electrical grid with TT earthing



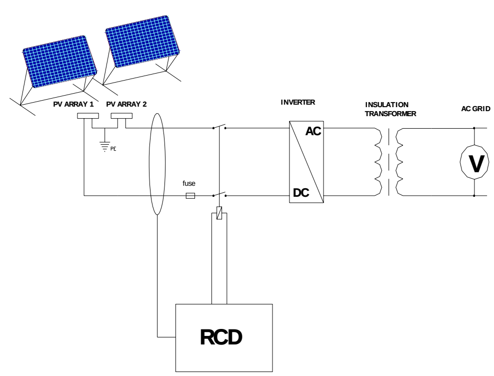
2 A PV DC bus system with RCD

In a typical AC residential distribution system the star point of the power source or distribution transformer and the protective enclosure is earthed (fig. 2). This protection system is called a TT electrical protection system(fig.2).

A single insulation fault between a power line and the protective enclosure will cause a leakage current. This leakage current can be detected by a residual current detector (RCD) which will switch off the power in case of an insulation fault. Leakage current limits of 300 mA and 30 mA are typical. For application in a residential AC distribution grid the RCD protection is useful because it is able to locate and isolate the fault to one user or house.

A similar system can be installed in DC bus systems, e.g. a photovoltaic (PV) grid coupled system with DC bus and inverter with transformer (fig. 3). The transformer provides galvanic insulation from the distribution grid. This insulation transformer is mostly integrated in the inverter. In this case an insulation fault on the DC bus will not propagate to the AC distribution grid. By consequence the DC bus needs to be protected and this can be done with a RCD. Therefore the star point of the PV array needs to be earthed. A DC RCD can be installed and will detect any single insulation failure caused after the RCD. In this system a failure is only detected after the RCD and thus not in one side, e.g. the DC source or PV panel itself which is a serious disadvantage for PV applications. The RCD technology for DC systems is also quite complicated because a DC current measurement transformer has to be used. RCDs could be installed in multiple locations in the DC bus and they would be capable of locating faults but this features is not very useful for PV applications. An insulation failure caused by human contact will result in human electrocution due to the current flow and a first contact failure is therefore unsafe. A symmetric insulation fault is one with an identical insulation failure on the positive and negative voltage terminal. This kind of fault is not detected with an RCD because both currents are identical(+ and -).

Fig.3 PV system with RCD protection and inverter with transformer



3 A PV DC bus system with IMD

The operation of insulation safety devices is already well-known [2, 3]. They are regularly used in AC industrial electrical distribution systems and are called IT protection systems (fig. 1). The power sources or distribution transformer is unearthed or

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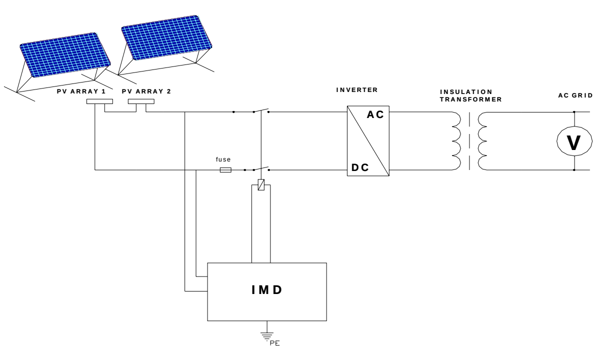
floating and the protective enclosure is earthed. The insulation monitoring device (IMD) measures the insulation resistance between the power lines and protective enclosure and switches off power in case of failure. Insulation resistance limits are typically between 30 and 100 kOhm.

A similar system can be installed in a DC voltage distribution system, e.g. a photovoltaic (PV) grid coupled system (fig. 4). These systems must be galvanic insulated from the distribution grid with an insulation transformer. In this case the distribution grid can be protected with an IMD. The insulation transformer will prevent the propagation of failures from the DC bus or PV panels to the AC distribution grid. The complete PV array and DC bus must be unearthed or connected to earth with a high impedance of at least 50 kOhm. The IMD will detect an insulation failure anywhere in the system, thus before and after the location where the IMD is installed. This is a very practical feature and makes an IMD more practical then RCD for PV systems. In a DC system the IMD can be constructed easily (see § 4). Because the system is floating or unearthed, human contact insulation failure with one of the terminals will not cause high levels of current flow and electrocution will not be experienced .

Fig.4: PV system with IMD protection

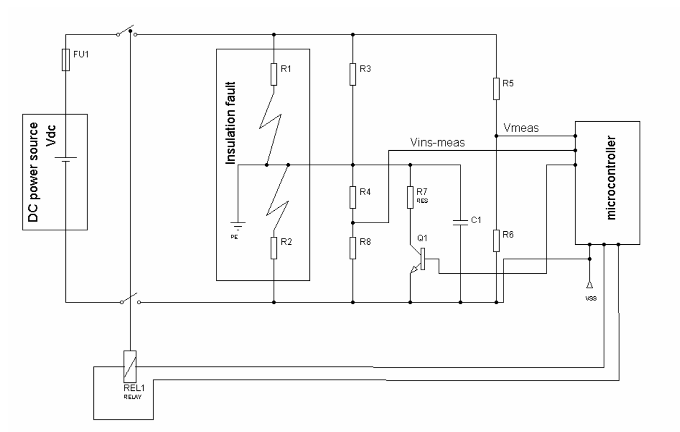


4 The DCSafe IMD system

Fig. 5 shows a schematic drawing of the DCSafe ® insulation monitoring function[15]. This system is very compact and can be easily integrated with other devices(e.g. inverter).

The microcontroller controls switch Q1 to the 'on' or 'off' state. Depending on the state, two voltages (Vm1 and Vm2) are measured. An additional voltage measurement is done for measuring the DC voltage produced by the source. Different insulation faults (Ri) are simulated. The unknown insulation resistance values of R1, R2 and R1//R2 are calculated[15] on the basis of the voltage measurements (Vins-meas1, Vins-meas2 and Vmeas) by the microcontroller. This microcontroller also allows the integration of other monitoring functions [8], undervoltage, monitoring, etc...

Fig.5: Schematic drawing of DCSafe ® insulation monitoring function (patent pending).



A PV test was set up and used for the simulation of insulation faults. These panels have an output voltage of +/- 113 Volt. Insulation faults were created on the +, the – and both terminals of the solar panel and at intermediate voltage (0 V) of the solar panel. The test results are shown in table 1.

From these experiments (table 1) we can conclude that the monitoring also works when an insulation fault occurs on an intermediate voltage of the solar panel and with a symmetrical fault on the + and – terminal of the solar panel. The calculated value of the parallel resistance (R1//R2) gives, in this case, the alarm level for an insulation fault.

5 Advanced and basic IMD systems

There are many IMD devices available on the market [8]. The basic IMD system measures an insulation fault in the complete system independent of its location, this is particular interesting in small grid applications (e.g. PV). More advanced IMD systems can also locate and isolate separate sub circuit faults [8]. They combine the IMD with an current measurement technique to locate the fault. Such complicated systems are mainly used in large industrial or medical electrical distribution systems.

6 Symmetric insulation fault detection with RCD and IMD

A symmetric insulation fault is one with an identical insulation failure on the positive and negative voltage terminal (e.g. fault 4 in table 1). In DC systems the like hood of this type of failure happening is not uncommon. A symmetric fault can also occur if there is a fault in the DC power source itself, at an intermediate voltage level in a stacked DC source (e.g. fault 5 in table 1). A symmetric fault is also introduced when the DC bus is loaded with a motor inverter and when an insulation failure occurs after the inverter (e.g. in an electric vehicle [8]). The IMD is able to detect all this faults(table I). An RCD can not detect a symmetric insulation fault because the induced leakage in the positive and negative conductor is identical.

7 Automatic disconnection of supply actions

If a first insulation fault occurs in an IT system and the fault current is limited in such a way that the dangerous touch voltage is less than the conventional voltage limit their must be no disconnection of this first fault. An alarm of the first fault can be given via LED and alarm contacts. It is important that this fault will be eliminated as soon as possible. If a second fault occurs before the elimination of the first fault, the system must be disconnected.

8 Comparison of IMD versus RCD

The discussed properties of the RCD and IMD techniques are compared and summarized in table 2.

Table 2: Comparison of RCD versus IMD DC bus safety system

		IMD	IMD	RCD
ref.	**Property**	**Basic**	**Advanced**	
1	failure detection in power source	yes	yes	no
2	failure detection in stacked DC sources	yes	yes	no
3	sensitive multilevel	yes	yes	no
4	fault location in complex distribution systems	no	yes	yes
5	symmetric fault (e.g. after motor inverter)	yes	yes	no
6	cost	low	high	medium
7	1st human contact cause electrocution(unsafe)	no	no	yes

9 EMC immunity tests on DCsafe IMD

Sources of voltage surges are numerous , but the most common and most well-known source is a lightning strike. Lightning transients may result from a direct strike or indirect from induced voltages and currents. IEC 61000-4-5 addresses the most severe transient conditions on both power and data lines. Electrical fast transients occur as a result of arcing contacts in switches and relays. IEC 61000-4-4 specifies the EFT threat in both power and data lines.

The DCsafe insulation monitoring device was tested to the immunity of surges and transients. Therefore Electrical Fast Transients of 2 kV and Surges of 1 kV (Line to line) and 2 kV (Line to Earth) were generated by the Transient 1000 generator. The insulation monitoring device continues to operate as intended (performance criterium B).

Table 1: Test results of different simulated insulation faults (Ri)

Ri KΩ	fault ref.	Location	Source V	Vm1 V	Vm2 V	R1 kΩ	R2 kΩ	R1 // R2 kΩ
30	1	+ terminal	111.6	0.996	0.75	32	4359	32
30	2	- terminal	113.5	0.222	0.17	2671	29	29
30 10	3	+ terminal - terminal	110.4	0.313	0.28	38	12	8.9
30 30	4	+ terminal - terminal	113.9	0.823	0.699	20	55	14
30	5	Intermediate (0V)	113.9	0.618	0.472	61	59	30

10 Conclusions

Finally it can be concluded that the IMD offers more features(table 1) then RCD for energy systems with DC bus voltages exceeding 75 VDC. The basic IMD is the ideal choice for small power grid applications with one central protection device. The DCSafe basic IMD is particularly interesting because it is compact and can integrate other monitoring functions in the microcontroller or can be embedded in the application(e.g. inverter). For larger DC bus systems where fault location is important advanced IMD techniques can be used.

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