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Insulation Fault Detection and Localisation in Electric and Hybrid Electric Vehicles

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Abstract—This paper discusses a method for detection and localisation of the insulation faults in electrical equipment distributed along the body of electric and hybrid electric vehicles. At the beginning of the fault detection procedure it is required that the vehicle powertrain be shut-down. The method is based on measurement and comparison of leakage currents in every device in the electrical powertrain. The leakage currents are generated by a high voltage signal generator connected between the vehicle body ground and dc-bus wires and shifting the potential between the electrical equipment and chassis. The currents are measured using a current clamp to detect the active component of the leakage current corresponding to an insulation fault. The proposed method was implemented in a prototype device used to detect an insulation fault in subway powertrains (i.e. a metro train). The method demonstrated excellent efficiency through successful detection and localisation of insulation faults.

Index Terms—Current transformers, Electric vehicles, Insulation testing, Leakage currents, Vehicle safety.

I. INTRODUCTION

The powertrain of modern electric and hybrid electric vehicles consists of many components, such as traction drives, generators, batteries, super-caps, power converters, and braking resistors etc. All these devices are very often connected using a high voltage dc bus (rated usually from 400 to 1000 V) and distributed along the vehicle body. Safe and reliable operation of the vehicle having a high voltage dc bus depends on the quality of electrical insulation between electrical and electronic components and the chassis ground. The vehicle operation in a harsh environment under vibration, corrosion, temperature and humidity change conditions significantly. This affects the quality of insulation and increase the risk of insulation failure [1],[2].

A conventional method of insulation monitoring is based on the measurement of voltage from a voltage divider connected to the chassis ground and the neutral point [6]. If any electrical part of the powertrain has an insulation fault then the potential of the neutral point is changed. This voltage can be measured and processed to detect an insulation fault and provide an alarm and information regarding the required fault recovery. This method can detect the insulation fault occurrence somewhere inside the powertrain but can not provide the exact fault location [3]-[6]. This paper discusses a method of detection and localisation of insulation faults in electrical equipment distributed over the vehicle body. The method has been implemented and successfully tested on a real powertrain.

II. PROBLEM DEFINITION

An example of the structure of the hybrid electric powertrain is shown in Fig. 1 [7]. This powertrain contains internal combustion engine, electric generator, rectifier, high voltage dc-link, inverters for traction motors and power converter for super-capacitor kinetic energy reuse system. The electrical equipment of the electric and hybrid electric powertrains is isolated from the chassis ground when the vehicle is operating under normal condition.

The insulation problems may occur in any part of this distributed powertrain. The dc-link wires are installed along the vehicle to connect several electrical machines and power converter. The cables from the power converters to the motors will bring even more problems if the motor-wheel design is used — these cables will be affected by the suspension travelling.
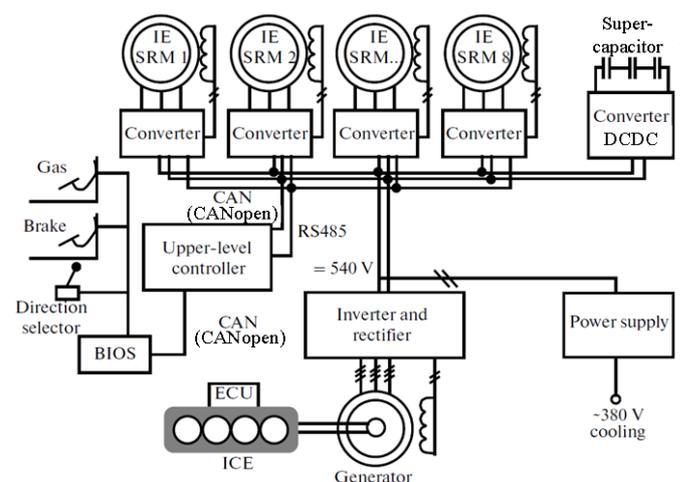

Fig. 1. Example of the structure of the hybrid electric powertrain (IE SRM – independently excited switched reluctance machine, ICE – internal combustion engine, ECU – electronic control unit).

The insulation fault detector based on the voltage divider operates on-line providing the information about insulation state of the whole vehicle. It can only confirm that the insulation is good, or there are problems somewhere in one of the devices of the vehicle.

If the insulation fault occurs it is crucial to determine the exact location of the faulty device. The conventional way to find the faulty component is to disconnect all the devices from the dc-link, and then to connect them back one after another. The appearance of the insulation fault will indicate the faulty component which is actually the last connected device.

However this method can not be applied for the insulation fault detection if the fault is occurred at a particular vehicle mechanism position or due to its movement. For example, under certain position a mechanical moving part can produce an electrical contact with conducting part of electrical device. In this case the insulation fault can not be localised.

Another disadvantage of the conventional approach is that the method is time consuming — the complete procedure is quite long. At the beginning the powertrain should be shut-down, all devices should be disconnected from the dc-link, and the circuits should be turned off by means of the mechanical switch or fuse removal. Then the powertrain is to be turned-on to the operation condition to start conducting the fault detection procedure. If the fault is not detected, then the powertrain is to be shut-down again and one device is to be connected back and so on. The more complex is the vehicle, the longer it takes to detect and localise the insulation fault.

III. LEAKAGE CURRENT MEASUREMENT FOR INSULATION RESISTANCE ESTIMATION

The suggested method aims to reduce time and improve efficiency of insulation fault detection and localisation procedure. Fig. 2 shows a functional diagram of the proposed approach. Advantage of the method is that at the beginning of the fault detection procedure the vehicle powertrain is required to be shut-down. According the method a signal generator is connected between the chassis ground and any point of the dc bus. The generator is to produce an ac voltage from 200 to 400 V. The output frequency can vary from 50 to 200 Hz. As the required output power is quite low the signal generator can be a portable powered from a low-voltage battery. The voltage is inverted and passes through a step-up transformer and a sine-filter. This voltage applied between a dc bus and chassis ground changes the potential of the powertrain equipment with respect to the ground point.

The change of the potential results in appearance of the leakage current to be measured using a handheld current clamp attached to the terminals on each device as can be seen in Fig. 2. The reason of use of ac voltage in this approach is that the current clamp can measure ac current only.

The electrical equipment distributed over the vehicle body has a significant total capacitance between conductors and the chassis ground. If the signal generator produces a few hundred volts between the conductor and ground then the capacitance current can be up to several mAmps. The insulation fault brings a reduction in active resistance between affected electrical circuit and the chassis ground. Therefore the measurement of a leakage current and comparison its phase shift to a normal capacitance current can be used to detect an insulation fault location.

The current clamp should be sensitive to measure currents from 1 mA and smaller. The standard current clamp resolution is limited by 10 or 100 mA, therefore the input amplification circuit should be redesigned to measure smaller currents.

To detect the device having insulation problems the current clamp should measure the leakage current in the mains of every device of the powertrain as shown in Fig. 2. The faulty device shows a higher leakage current which helps to localise an insulation fault.

From first tests results it was found that all devices in the powertrain have relatively big parasitic capacitance between the conducting parts and the chassis ground. This capacitance is caused by the presence of the EMI filters, capacitance of the motor windings to the grounded iron, capacitance of the dc-link bus to the chassis. For the vehicle with the sizes of the subway car this capacitance can reach 100 nF and more. This gives more than 10 mA of the capacitance current which is not corresponds with the insulation fault.
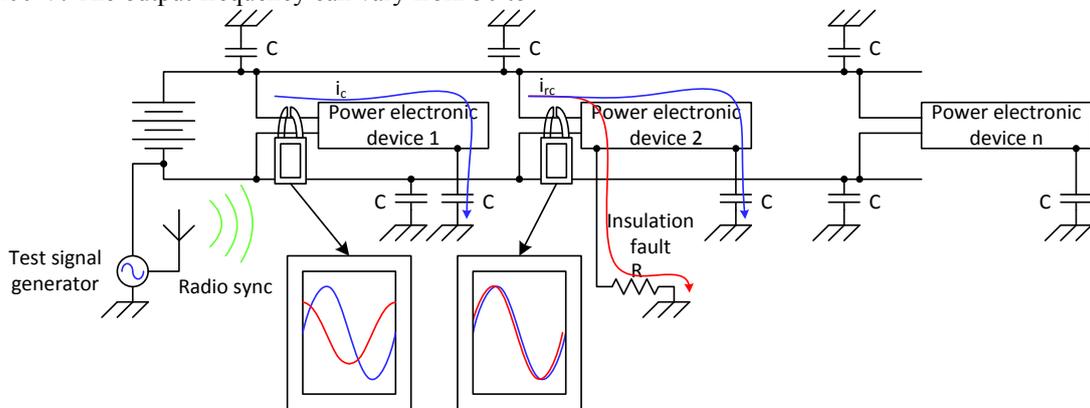

Fig. 2. Functional diagram for insulation diagnostic system.

To distinguish the capacitance current from the insulation fault the phase of the current should be examined. So it is needed to know the phase of the generator voltage and the phase of the measured current. This task requires major modification of the test hardware.

There are two different approaches which can be applied to synchronise the generator and the current clamp circuit in order to conduct the phase shift measurement. First approach, currently implemented in the proto-type, is based on wired or wireless communication. However the wired synchronisation is inconvenient due to length of vehicle body and problems with tangle of the wires between the generator and the leakage current sensor. The wireless synchronisation is much convenient. The generator forms sinusoidal voltage and airs a clock signal corresponding to every cycle of the test voltage. The current clamp measures leakage current at the time synchronised to a received clock pulse and determines active and reactive components.

The second method of synchronisation is based on Fourier transform and do not use the wireless communication. The generator forms 1st and 3rd harmonics or simply square waveform voltage. The 1st and 3rd harmonics of the leakage current have the different phase shift if the measured current comprises of active or reactive component only. Although this method does not require the radio channel, the analysis of the harmonic components gives currently inaccurate phase measurement due to small magnitudes of the signal. This method will be investigated in the future.

The current clamp sensor was completely redesigned. The new PCB includes radio receiver, current measurement amplifier and LCD graphics display to indicate the current curve. The functional diagram for the current clamp is shown in Fig. 3.

The developed current clamp provides measurement of the leakage current from 0.4 mA which is corresponding to 1 MΩ at 400 V of testing voltage. To distinguish the capacitance current from the insulation fault the current clamp indicates active and reactive components of the leakage current separately. An example of the display of the clamp is shown in Fig. 4.

IV. CONCLUSIONS

The discussed method was implemented in a prototype device which has been used to detect an insulation fault in subway powertrains (i.e a metro train). The method demonstrated excellent efficiency through successful detection and localisation of the insulation faults. The detected faults are effectively pointed the device having faulty insulation and to be replaced.

However if the insulation fault occurs in the load of power converters the test signal has to be applied to a certain circuit. On the other hand this type of insulation fault can be detected by means of the power converter.
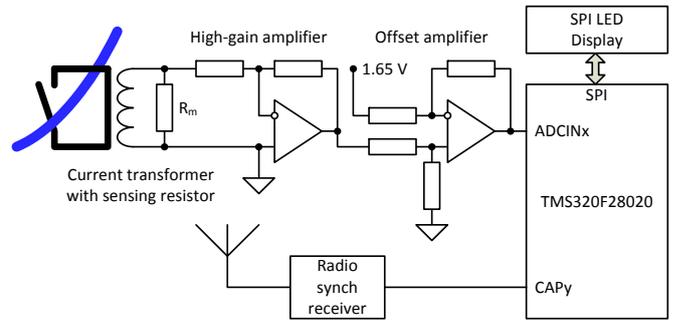

Fig. 3. Functional diagram for the current clamp.
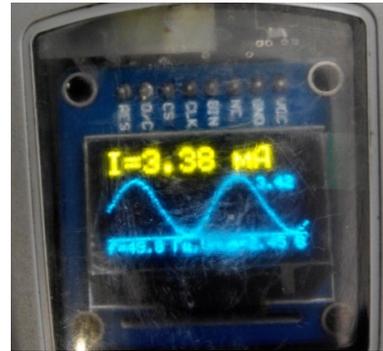
Fig. 4. Display of the current clamp.

The further investigations is planned to improve the phase detection for the square-waveform testing voltage to exclude the radio synchronisation circuits from the hardware.

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