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Low Voltage Prototype Design, Fabrication and Testing of Ultra-Fast Disconnector (UFD) for Hybrid DC CB

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SUMMARY

Direct current Circuit Breakers (DC CB) are vital components for DC grids and the Hybrid DC CB is of high interest because of fast operating speed and low on state losses. The speed of operation of hybrid DC CB is crucially determined by the speed of Ultra-Fast Disconnector (UFD). This article presents in some detail design, fabrication and testing of a low voltage UFD at a University laboratory. The UFD is designed to operate in 2ms and separates the contacts by 3.0mm, which is adequate to withstand a voltage level of 7kV in air. The contacts of the UFD are designed to carry a rated current of 100A. The speed requirements demand a driver capable of supplying a current pulse of few kA, which is achieved using capacitive storage. The experimental measurements show that the UFD is capable of opening and closing in around 1.8ms. Higher opening speeds are possible but bounce becomes pronounced. The paper also presents a method of magnetic braking which eliminates bounce and enables application of higher forces and the opening time of 1.3ms is demonstrated.
The speed of UFD open-close-open cycle is dependent on the charging time of the UFD driver circuit which is quite long because of large stored energy. It is concluded that at least two complete driver circuits are necessary.

KEYWORDS

Direct Current Circuit Breaker (DC CB), Ultra-Fast Disconnector (UFD), High Voltage DC (HVDC).

1 INTRODUCTION

The demand for HVDC transmission has been growing mainly because of the increased power trading, increased usage of large scale renewables in remote areas. Recently there has been significant advance in HVDC technology which have increased performance but reduced losses, costs and harmonics, and there is real prospect of building DC grids [1]-[2]. Direct current Circuit Breakers (DC CB) are vital components for DC grids, and they have been designed and prototyped in last few years [3], [4]. Different technologies of DC CB's (mechanical, solid state, and hybrid) are available but the Hybrid DC CB [3] has been of most interest because of fast operating speed and low losses. The speed of DC CB operation is the crucial performance factor and has significant impact on cost and performance of dc grid.

The hybrid DC CB consists of a) nominal current blanch with mechanical switch UFD (Ultrafast Disconnector) and load commutation switch, b) main breaker switch consisting of an IGBT valve and c) energy absorbers. The UFD crucially determines the speed of DC CB operation. In closed position UFD should have low conduction loss, while in open position it should create isolation in the DC CB normal current path. UFD can open only at zero current (it has no current interrupting capability).
The basic operating principles and performance expectations of ultrafast actuators are known [5], [6] although manufacturers have not revealed all design constraints of these new devices.
The objectives of this project are to build scaled laboratory demonstrator of UFD and explore physical limits in terms of speed of operation and re-closure time. The desired operating time is 2ms, with 7kV isolating voltage and 100A current carrying capacity.

2 UFD OPERATION PRINCIPLES AND CONSTRUCTION

Figure 1 shows the schematic of the designed UFD with all the main parts numbered. The fabricated UFD is shown in Figure 2.
The main parts of the UFD are, as labelled in Figure 1:

1- Bi-stable structures, labelled as “1”, which are used to hold the actuator disk in two stable positions (open or closed).
2- The TCs (Thomson coils) for closing operation, labelled as “2”. By energizing these two TCs forces are generated in the actuator disks and move them away from the energized TCs.
3- The TCs for opening operation, labelled as “3”. By energizing these two TCs forces are generated in the actuator disks and move rods with contacts away from one another.
4- Two actuator disks with rods, labelled as “4”. They conduct inducted currents which generate forces that move the actuator disks upwards or downwards.
5- The parts labelled as “5” are the contacts which are attached to the rods using insulators. The copper contactors make or break the electrical circuit.

When the UFD is in open position, the actuator disks are close to the TCs numbered 2 and the contacts are separated. For closing the UFD the TCs numbered 2 are energized and TC currents induce high current in the actuator disk. Interaction between the TC and actuator disk currents generate forces which push the actuator disks away from the TCs. The opening process is similar but TCs number 3 are energised.

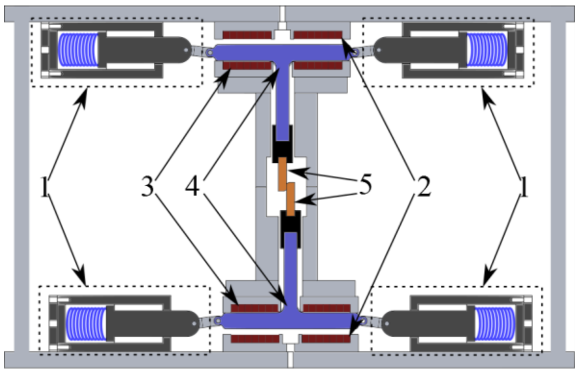

Figure 1 Schematic of the designed UFD

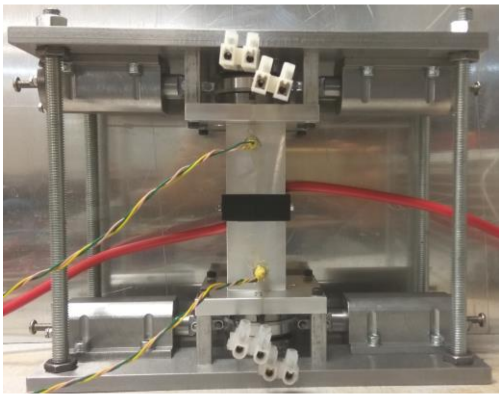
Figure 2 Fabricated UFD

3 UFD ELECTROMECHANICAL MODELLING

The electromagnetic energy in the TC is discussed in [5]-[7] and can be represented as:

$$E_{em} = \frac{1}{2}\left(L_{coil} I_{coil}^2 + L_{arm} I_{arm}^2 - 2M I_{coil} I_{arm}\right) \quad (1)$$

Where L_{coil} and L_{arm} are the self-inductance of the TC and the actuator disk respectively. I_{coil} and I_{arm} are the TC current and the actuator disk induced currents respectively, and the M is mutual inductance between the TC and actuator disk. Figure 1 shows one (of four) assembled Thomson coils. The electromagnetic force can be obtained by differentiating of the electromagnetic energy in (1) [7].

$$F_{em} = \frac{dE_{em}}{dz} = -\frac{dM}{dz} I_{coil} I_{arm} \tag{2}$$

The force generated on the rod is balanced by the acceleration force, bi-stable springs F_{bis}, viscous friction Bv, static friction F_{fric}, and weight W_g,

$$F = m\frac{dv}{dt} + Bv + F_{fric} - F_{bis} \pm W_g \tag{3}$$

where B is the viscous friction coefficient, and m is the total moving mass. The above model is used for dimensioning UFD and a corresponding dynamic model is developed in PSCAD. The calculated UFD parameters are shown in Table 1.

Parameter	Label	Value
viscous friction	B	20Ns/m
static friction	F_{fric}	4N
Mutual inductance	M	0.2μH
Moving parts Weight	Wg	140g
Thomson coil turns	N	8.5turns
Actuator disc diameter	D	50mm
Copper contact s area	A	3.1mm^2
Bistable spring constant	K_{bis}	29.85

Table 1 UFD parameters

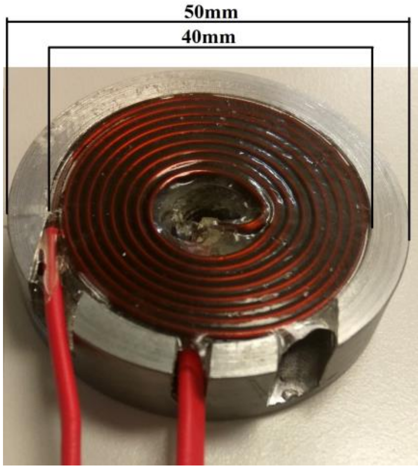

Figure 1 *Thomson coil*

4 UFD POWER SUPPLY

The desired operating time is *2ms* with separation distance of *3mm*, which requires very large acceleration which in turn demands significant electromagnetic force. The initial design study indicates that several kA current pulse is required. These pulse currents are supplied by the UFD power supply based on a storage capacitor, shown in Figure 1. The capacitor C_d is charged using a 100VA transformer Tr and a diode bridge rectifier. The charging is controlled by the Mosfet, T_{ch}, while resistance R limits the charging current. This power supply can supply two TC as shown in the figure. By triggering T_1 or T_2 the TC to be energized is selected. This power supply can work up to 200V and can supply a pulse current of up to 5kA. Another power supply is built for the remaining two TCs.

The fabricated UFD Power Supply is shown in Figure 2. The parameters of the UFD and the power supply is tabulated in Table 2

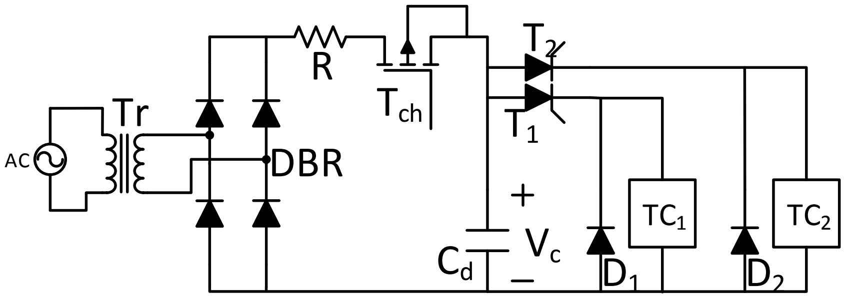

Figure 1 *UFD driver circuit.*

Parameter	Label	Value
Charging Resistor	R	2.2
Charging Mosfet	T_{ch}	200V, 50A
Thyristor	T2, T1	1600V, 70A
Diode	D1, D2	600V, 80A
Capacitance	C_d	8.1mF
Rectifier	DBR	1000V, 50A
Transformer	Tr	100VA

Table 2 UFD driver parameters.

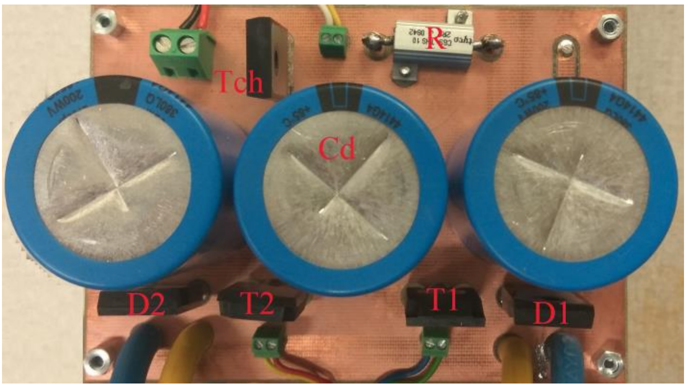

Figure 2 Fabricated UFD Power Supply.

5 Control system

To detect the position of the actuator disk and measurement of the operating time, hall sensors are used. A small magnet is attached to the actuator disk and a hall sensor is fixed stationary next to the magnet. The sensor gives voltage signal proportional to the position of the rod and this has proven to be sufficiently accurate to measure position of the contacts.

A simple PWM feedback controller regulates capacitor voltage Vc, once capacitors are discharged. The TC current pulse is initiated by firing a thyristor.

6 Experimental results

The experimental measurements of the closing operation are shown in Figure 1. The closing command is send to the UFD at time 0. The position sensor output (yellow) shows zero at t=0, which indicates open position. The position output of 3mm indicates that the UFD is fully closed. It can be seen that the UFD closes in 1.8ms. The capacitor voltage discharges in 300µs as shown by the blue curve. The peak TC current is around 2.94kA as shown by the red curve.

The UFD opening operation is shown in Figure 2. The opening command is send to the UFD at time 0. The UFD reaches fully open position in 1.8ms. Examining the position curve, it can be seen that the actuator disk has a slight bounce of around 200µm. The applied driver voltage of 120V is the maximum value that results in an acceptable bounce.

The UFD has been tested at different driver voltage from 90V to 170V and the opening time is measured, in order to explore possible increase in the operating speed. For voltages over 120V bounce is pronounced but it is assumed that bounce can be eliminated in other ways. The results are shown in

Figure 3. It can be seen that the UFD operates in 3.7ms if the UFD power supply capacitors are charged up to 90V. As the capacitor voltage is increased the UFD operates faster. It can be observed that increasing the capacitor voltage from 90V to 130V reduces the operating time from 3.7ms to 1.5ms. In this case the input voltage is increased by 44.4% and results in operation time reduction of 59.5%. If the capacitor voltage is increased further by 30% to 170V the operation time reduces by 28% to 1.08ms. If the UFD is to operate in 2ms, the capacitor voltage should be 115V.

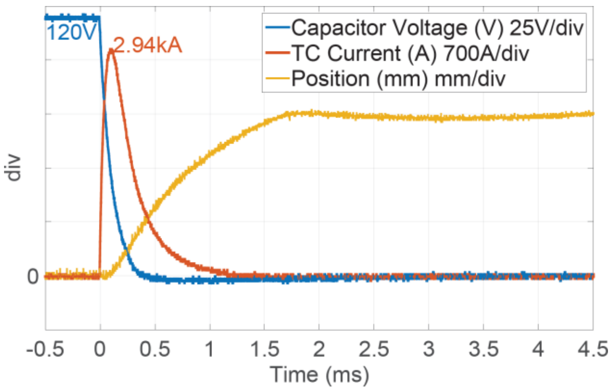

Figure 1 UFD closing operation with driver voltage of 120V.

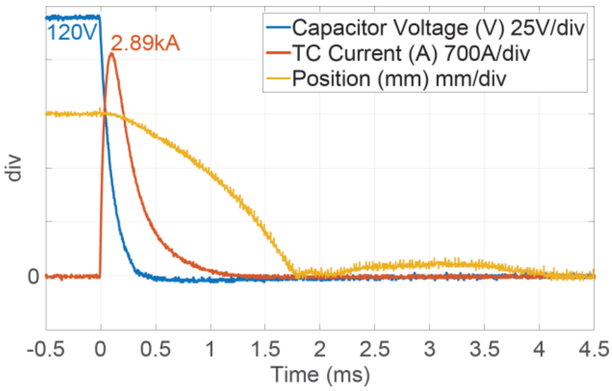

Figure 2 UFD opening operation with driver voltage of 120V.

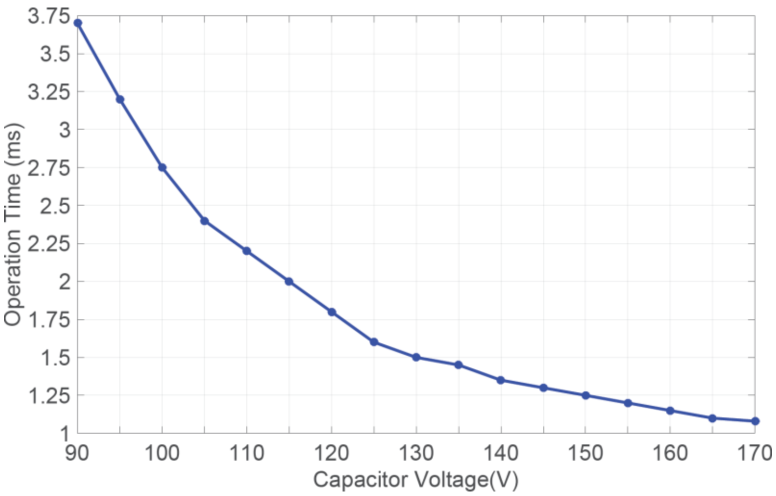

Figure 3 UFD opening time versus applied driver voltage.

7 IMPROVING OPENING SPEED USING ELECTROMAGNETIC BRAKING

If the UFD is operated faster, the bounce becomes significant. Figure 1 shows experimental results with 140V driver voltage which results in around 40% bounce (1.3mm). This is not acceptable as it results in the lower withstand voltage of UFD and may results in arcing.

The bounce problem has been recognised by manufacturers and pneumatic damping is achieved with the insulating SF6 gas in the initial designs [6]. Our UFD uses open air as insulator and therefore different methods are studied.

Electromagnetic Braking (EMB) is a braking mechanism which creates a counter force at the end of traveling of the actuator disk. This reduces the speed of the actuator disk and hence, reduces the bounce effectively. The procedure for EMB is as follows:

1. The opening TC is energized and the position sensor output is monitored.
2. Once the position sensor reaches the threshold, the closing TC is energized with lower voltage. The voltage magnitude and instant of EMB is determined experimentally.

The experimental results for opening with EMB are shown in Figure 2. It can be seen that he EMB effectively eliminate the bounce and the UFD can operate in around 1.3ms. The observed bounce is around *200μm* which is within the acceptable margin.

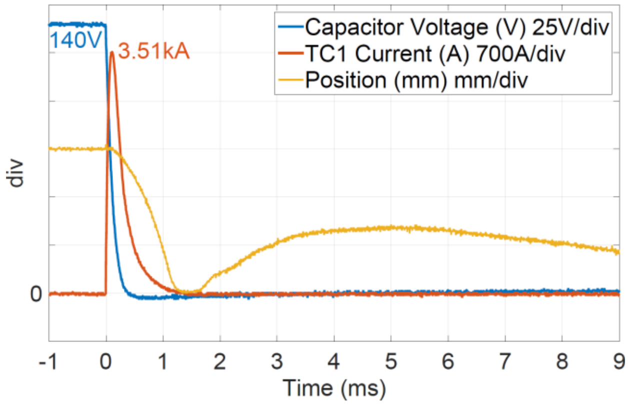

Figure 1 UFD opening with driver voltage of 140V.

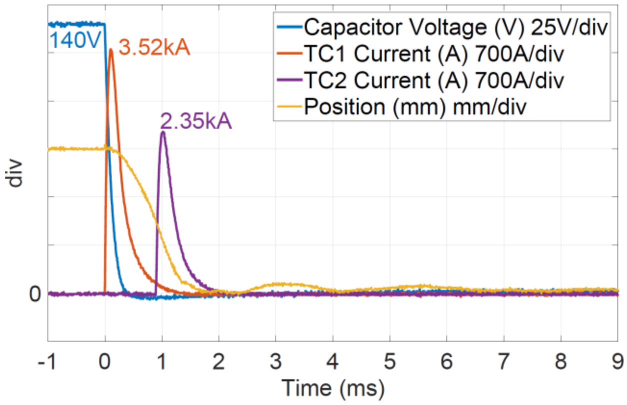

Figure 2 UFD opening with driver voltage of 140V and magnetic braking.

8 Operating cycle time-constraints

The charging time for the driver capacitor is about 3s since the employed transformer and diode bridge have current rating of around 30A. Consequently, there is 3s constraint on the time between each operation of the developed UFD. In practice it may be desired to have open-t_1-close-t_2-open cycle with smaller values for times t_1 and t_2, although standards for DCCBs do not exist yet.

The speed of open-close-open cycle can be enhanced in several ways:

1. The simplest way is to increase the charging capability by using bigger transformer and rectifier. Only limited improvement is possible.
2. Introduce another complete driver for the second operation. Hence, for next operation there is a charged capacitor available which can energize the TCs. Depending on the required number of operations, multiple driver sys6ems may be needed.
3. In hybrid DCCBs it is possible to bypass UFD with the main breaker valve. Depending on heat dissipation capability of the main valve, the closing UFD operation can be delayed. However it is not possible to delay UFD opening operation, and therefore it seems that two UFD drivers will always be required.

9 Conclusion

A 7kV, 100A UFD with 2ms operating time is designed and fabricated in the university laboratory. The speed requirements demand a driver capable of supplying a current pulse of few kA, which is achieved using capacitive storage. The experimental measurements show that the UFD is capable of opening and closing in around 1.8ms with a negligible bounce.
The operation time can be improved by increasing the UFD power supply voltage. The experimental measurements indicate that opening speed of 1.1ms is feasible, although bounce would be significant in such case.
An electromagnetic braking is studied in order to eliminate the bounce at high opening speeds. The experimental results show that the operating time of 1.3ms is achieved when magnetic braking is used.
The speed of open-close-open cycle is dependent on the charging tie of the UFD driver circuit, and it is concluded that at least two complete driver circuits are necessary.

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