

Determination of Equivalent Circuit Parameters of Supercapacitor and its Testing with Three Phase Inverter

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Abstract

Supercapacitor technology has been available commercially for over the past decade. They can store more energy than conventional capacitors and are available in various sizes. They can be charged and discharged faster than batteries. Because of so many advantages such as high power cycling capacity, low maintenance and long service life, wide operating temperature and lowest internal Equivalent Series Resistance(ESR), supercapacitors are used for an unlimited number of applications nowadays. There is a strong need to gain a better understanding of supercapacitors when used in electric utility applications. This requires suitable models that can be incorporated into different software programs currently used to create dynamic simulations for applications such as MATLAB Simulink, PSPICE, PSCAD etc. This paper focuses on the use of charging and discharging tests to develop the equivalent circuit models to characterize symmetric supercapacitors for electric utility applications. Design, fabrication and testing of three phase IGBT based inverter is also done for interfacing with supercapacitor and grid. Control algorithm is implemented in PIC16F877a microcontroller. Results are presented in the paper, which show that supercapacitor is supplying real power needed by the load and losses of the inverter.

Keywords: Supercapacitor, Equivalent Series Resistance, Capacitance, Charging and Discharging tests

Introduction

There are three general classifications of capacitors - electrostatic, electrolytic and electrochemical capacitors[3]. Electrochemical capacitors are further grouped into two major categories-symmetric and asymmetric. Symmetric Electrochemical capacitors (ECs) use same electrode material for both positive and negative electrodes. They get their electrostatic charge from the accumulation and separation of ions at the interface between the electrolyte and electrode. Over the years, ECs have acquired many names such as super capacitor, ultra capacitor, Pseudo capacitor, Double layer capacitor etc. Symmetric ECs can use aqueous or organic electrolyte solutions. Aqueous electrolyte allows a maximum voltage of 1V per cell. If an organic electrolyte is used, the maximum allowable voltage per cell is 2.5V. A number of ultracapacitor cells are connected to form an Ultracapacitor module. Fig.1 shows the schematic diagram of an Ultracapacitor module.

An ultracapacitor is an electrochemical device consisting of two porous electrodes immersed in an electrolyte solution that stores charge electrostatically. It stores electrical charge in an electric double layer at the interface between a high surface area carbon electrodes and a liquid electrolyte. Electric double layer concept was first described by Hermann Von Helmholtz in 1853. Supercapacitors are essentially a high power density energy storage technology. High capacitance is achieved by reducing plate separation to a few Angstroms by using an electrochemical double layer and also by increasing the plate surface area by use of high surface area carbon electrodes. Supercapacitors also called as ultra capacitors or electric double layers capacitors have been the subject of focused research and development efforts for past two decades. These devices can be manufactured with capacitance values of several hundred farads, unimaginable in conventional capacitors. Supercapacitors integrated with a power conversion system can be used to assist the electric utility by providing voltage support, power factor correction, active filtering, and reactive and active power support. Supercapacitors are attractive for utility applications because they have higher energy density than conventional capacitors and higher power density than batteries. They also have higher cycle life than batteries, which results in longer life span.

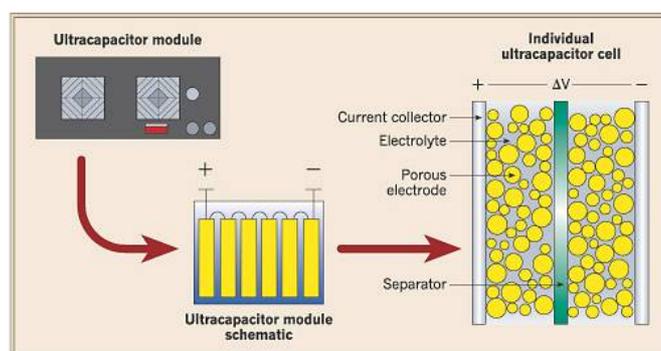


Figure 1: Schematic diagram of an Ultracapacitor module.

Comparison of Electrochemical Super Capacitors

Nowadays, there are three groups of super capacitors which are commercially available such as Carbon/carbon with aqueous electrolyte, Carbon/carbon with non-aqueous electrolyte and Carbon/MeOx with aqueous electrolyte[3]. First two groups belong to symmetrical super capacitors and third group belong to asymmetrical super capacitor. Based on the operation parameters such as response time, compactness and efficiency of energy transformation only first group meets all the requirements. Second group of super capacitors donot have acceptable response time. They are also limited by currents of emergency charge because of heating. Third group of super capacitors have ideal non-polarized electrodes where charge current is limited by efficiency of charge of Faradaic electrode. As for reliability and safety parameters, all electrochemical super capacitors ensure necessary shock ressitance and service life. Third group has limited stability to short circuit but not stable to reversed polarity because of uncontrolled hydrogen emission on Faradaic electrode., which can cause super capacitor module explosion. Second group of supercapacitors with non-aqueous electrolyte can be stable to short circuit but they cannot resist long 50% over voltage charging. It results in either explosive electrolyte vapour emission through emergency valve or explosion of capacitor body. This group with “dirty” organics and sometimes with flammable and highly explosive acetonitrile donot meet ecological requirements in many countries, whereas third group super capacitors are more acceptable from ecological point of view, despite of nickel or lead components. First group have practically no restrictions for them to be used anywhere. Summarizing, only one type of electrochemical systems corresponds completely to specific Power Quality requirements-Carbon/carbon super capacitors with aqueous solution of electrolyte.

Three kinds of construction are widespread among super capacitor manufacturers such as single cells of high capacity with rolled electrodes, single cells of high capacity with flat electrodes and bipolar systems with electrodes of low capacity[3]. The first two types have a separate current circuit-electrode or block of electrodes to terminal, which occupies upto 30% of capacitor volume. Bipolar systems have no external circuit of cell, the current goes through all electrode cross-section of cells perpendicularly to normal .In addition to decrease of occupied volume, it gives one main advantage-decrease of ESR in circuit of electrode to external terminal. Thus bipolar systems are the most compact among all the design solutions. Practical response time for bipolar systems with aqueous electrolyte is less than 40 microseconds at peaks of maximum discharge current. Series connected super capacitors have high enough RC time constant. So, it can be said that bipolar systems with aqueous electrolyte are approximately 20-25 times more effective in charge/discharge process when compared to single cells of high capacity with non-aqueous electrolyte. All types of ultracapacitors are practically stable for shock resistance. Thus the best way to realize power quality solutions is to use super capacitors with bipolar design.

Stability of high voltage circuit during operation is influenced by spread of capacity, ESR and leakage current of single cells[3]. Industrial manufacturers use various kinds of voltage leveling for separate cells in circuit. The simplest way is passive regulation by shunting each cell in circuit by resistor. This causes parasitic

energy losses. Active regulation with energy pumping does not cause parasitic losses but it is more complicated technically. As applied to super capacitor designs, active regulation can be successfully used with cells of big capacity and passive one with cells of small capacity. The active control of cell group and passive regulation in an individual cell is preferable for bipolar design. Stability in high voltage is also influenced by the type of the electrolyte used. Researches showed that high voltage super capacitor modules with aqueous electrolyte are more stable against long floating operation than super capacitor with non-aqueous electrolyte. So, it can be concluded that Electrochemical supercapacitors of bipolar design of carbon-carbon system with aqueous KOH solution with embedded system of combined voltage regulation and valves for oxygen gassing are best for power quality solutions.

Determination of Equivalent Circuit Parameters of Supercapacitor

A supercapacitor can be modeled in a similar manner to conventional capacitors. There are many models developed to characterize the electrical behavior of supercapacitor[1].The multi branch model defines the capacitance of the supercapacitor as a constant capacitor with a parallel capacitor dependent on voltage. This voltage dependence capacitance implies that more energy can be stored in it than expected The transmission line model is a complex network of non-linear capacitors connected between them by resistors. Fig. 2 shows the classical model of supercapacitor, where ESR is equivalent series resistance, C is the capacitance and EPR is the equivalent parallel resistance of supercapacitor.

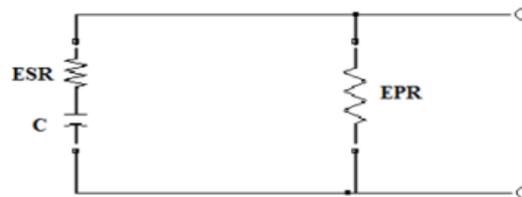


Figure 2: Classical model of supercapacitor.

In short, the most important parameters of a supercapacitor include capacitance, ESR and EPR. Capacitance decides the energy capability that can be stored in a supercapacitor. ESR consists of electrode resistance, electrolyte resistance and contact resistance and wastes power for internal heating when charging or discharging. For the supercapacitor, ESR is less than one milliohm but influences the energy efficiency and power density. EPR is an inner equivalent parallel resistance usually in hundreds of kilo ohms and decides the leakage current when the supercapacitor is in stand-by-mode. A. ESR MEASUREMENT

There are two methods available for the determination of ESR of supercapacitor[2].The first method is a voltage decline at the beginning of the discharging as shown in Fig. Initially the supercapacitor is charged to the rated

voltage and then it is discharged. Instantaneous voltage drop and currents are recorded by two probes of an oscillograph. The voltage drop and discharging current can be measured through resistor sampling. The ESR is the quotient of voltage drop to discharge current. The second one is constant current charging method. After discharging the supercapacitor thoroughly, it is left for a long time and charged by AC current source. The voltage across the supercapacitor is just the ESR voltage drop because the capacitive component is equivalent to short circuit to ac signals. If a DC current source is used, the voltage will increase from a specified value other than zero. This initial value is the ESR voltage.

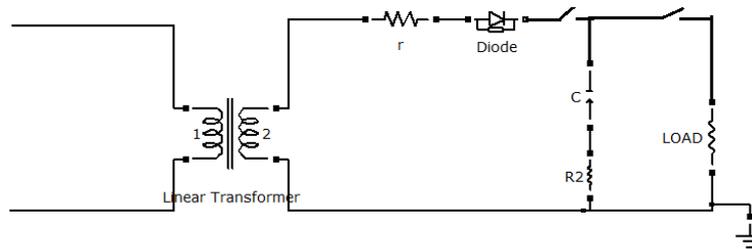


Figure 3: Experimental circuit to find ESR by voltage drop method.

EPR Measurement

When the supercapacitor is charged to a specified voltage, the power supply is disconnected and left in the self discharging state. The voltage of supercapacitor declines approximately according to equation

$$U=U_0e^{(-t/RC)}$$

Where U_0 and U are the voltages of the supercapacitor before and after discharging respectively, R and C are its resistance and capacitance respectively and t is the discharging time. EPR in ohms is given by

$$EPR=-(t_2-t_1)/ (\ln (U_2/U_1)*C)$$

Where U_1 and U_2 are the voltages at t_1 and t_2 respectively, C is the supercapacitor’s rated capacitance in Farads. EPR varies with the environment temperature. Self discharging becomes more serious when temperature rises.

Capacitance Measurement

Supercapacitor is charged to full rated voltage. Then it is allowed to discharge through a known value of resistance and the time taken for the rated voltage to reduce to half the rated value is noted using stop watch. Then the capacitance in farads is calculated using the equation

$$C= t/(R \times \ln 2)$$

Where t is the discharge time and R is the known load resistance in ohms.

Test Results

Fig 4 shows the supercapacitors available in Aartech Solonics Ltd., Bhopal. Following six different supercapacitors are chosen for study (i) Kranking 100PP14 (ii) Kranking 15PP3 (iii) Kranking 15PP1 (iv)Kranking 24PP30 (v) Faradigm 2.4V, 3.3F (vi)Faradigm 2.4V, 1F. All these supercapacitors are of symmetric type whose electrodes are made of carbon. First four types use aqueous KOH (potassium hydroxide) electrolyte and last two types use organic electrolyte.



Figure 4: Different types of supercapacitors.

The individual cells in the module are connected in series and parallel to get the desired voltage and capacitance. Equivalent circuit parameters of supercapacitor were obtained from charging and discharging tests.

Testing Of 100PP14

100PP14 supercapacitor is charged to the rated voltage of 100V from an AC source through an autotransformer. A filter capacitance of 470 microfarad and 250V is used to remove ripples in DC voltage output. Once it reaches the rated voltage, supercapacitor is discharged through a load resistance of 28.6 ohms, 250W. Fig. 5 shows the charging and discharging set up of the super capacitor. Fig. 6 shows the charging and discharging characteristics of 100PP14. Table 1 and 2 show the results. From the results, 100PP14 supercapacitor's equivalent circuit parameters are found to be

$$C_{\text{CALC}} = 3.278 \text{ F}$$

$$\text{DC ESR} = 0.125 \, \Omega$$

$$\text{DC EPR} = 5398.166 \, \Omega.$$



Figure 5: Charging and Discharging set up of 100PP14.

Table 1: Self discharge results of 100PP14.

TIME(s)	VOLTAGE(V)
0	100
240	96.9
600	95

Table 2: Charge and discharge results of 100PP14.

Transient Voltage drop(V)	Current(A)	Time to discharge to half the rated voltage(s)	Load resistance (Ω)
0.44	3.496	65	28.6

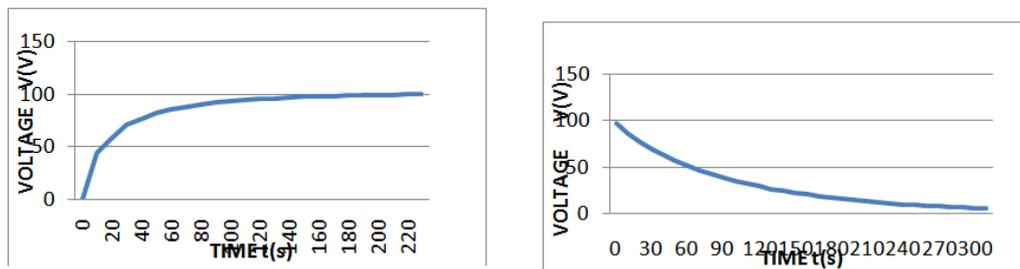


Figure 6: Charging and Discharging characteristics of 100PP14.

Testing Of 15PP3

The following graphs show the results obtained by testing the supercapacitor 15PP3. Here the supercapacitor is charged using a constant current charging of

10A. Then it is discharged through a 10 ohms, 200W load resistance. Fig.7 shows the charging and discharging characteristics and Table 3 and 4 show its results.

Table 3: Self discharge results of 15PP3.

TIME(s)	VOLTAGE(V)
0	12.25
180	12
360	11.75

Table 4: Charge and discharge results of 15PP3.

Transient Voltage drop(V)	Current(A)	Time to discharge to half the rated voltage(s)	Load resistance (Ω)
0.48	1.25	254	10

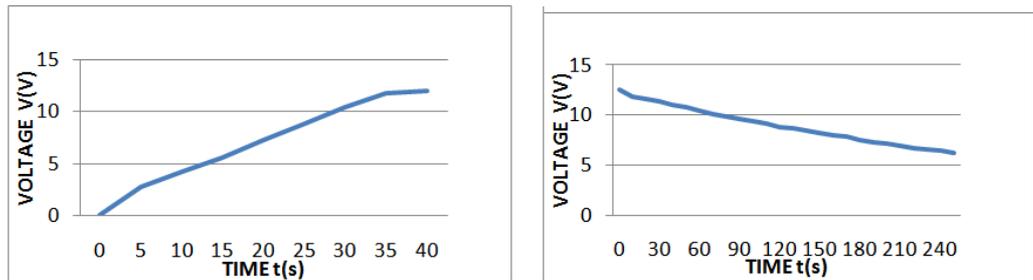


Figure 7: Charging and Discharging characteristics of 15PP3.

From the results, 15PP3 supercapacitor's equivalent circuit parameters are found to be

Parameters

$C_{CALC}=36.69F$

DC ESR = 0.192Ω

DC EPR = 371.26Ω

Testing Of 15PP1

The following graphs are obtained by testing supercapacitor 15PP1. Charging is done by a constant current of 10A and discharging is done through a load resistance of 10 ohms, 200W. Fig. 8 shows the charging and discharging characteristics. Table 5 and 6 show the results.

Table 5: Self discharge results of 15PP1.

TIME(s)	VOLTAGE(V)
0	12.5
180	12.4
360	12.32

Table 6: Charge and discharge results of 15PP1.

Transient Voltage drop(V)	Current(A)	Time to discharge to half the rated voltage(s)	Load resistance (Ω)
0.48	1.25	118	10

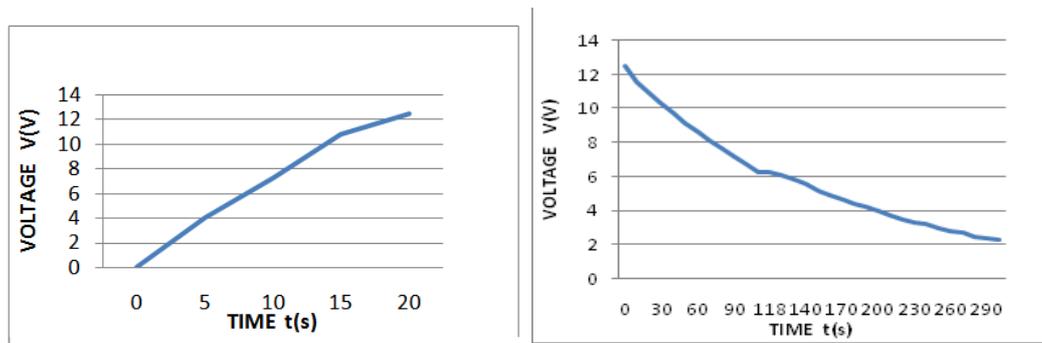


Figure 8: Charging and Discharging characteristics of 15PP1.

From the results, 15PP1 supercapacitor’s equivalent circuit parameters are found to be

EPR=1769.98 Ω

C_{CALC}=17.06F

ESR =0.192 Ω

Testing Of 24PP30

Fig. 9 shows the test set up for charging and discharging of supercapacitor 24PP30.



Figure 9: Constant current charging of 24PP30 super capacitor.

Fig. 10 show the charging and discharging characteristics and Tables 7 and 8 show the results obtained by testing the supercapacitor 24PP30.

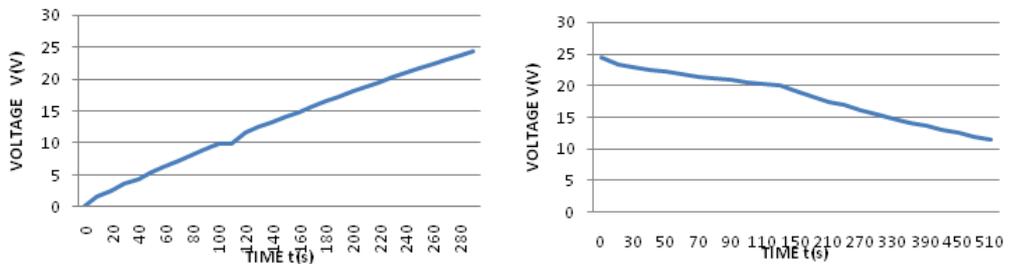


Figure 10: Charging and Discharging characteristics of 24PP30.

Table 7: Self discharge results of 24PP30.

TIME(s)	VOLTAGE(V)
0	23.8
120	23.5
390	23

Table 8: Charge and discharge results of 24PP30.

Transient Voltage drop(V)	Current(A)	Time to discharge to half the rated voltage(s)	Load resistance (Ω)
0.4	4.9	463	5

From the results,24PP30 supercapacitor’s equivalent circuit parameters are found to be

$$C_{CALC}=133.53F$$

$$ESR =0.08163 \Omega$$

$$EPR =112.4\Omega$$

Testing Of Faradigm 2.4V, 1F

The following graphs show the results obtained by testing the supercapacitor Faradigm 2.4V, 1F with a constant current charging of 0.27A and discharging through 5 ohms,200W load. Fig. 11 shows its charging and discharging characteristics of 2.4V,1F supercapacitor. Tables 9 and 10 show its results. From the results,2.4V,1F supercapacitor’s equivalent circuit parameters are found to be

$$C_{CALC}=1.44F$$

$$ESR =0.288 \Omega$$

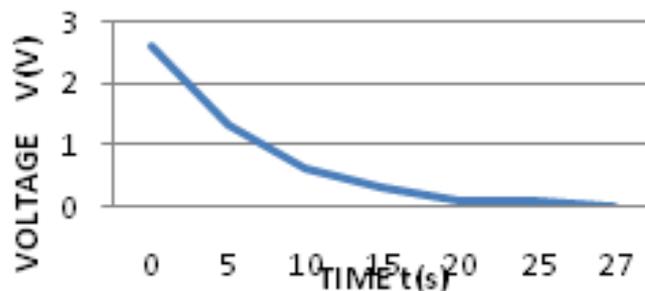
$$EPR=3224.29 \Omega$$

Table 9 : Self discharge results of 2.4V,1F.

TIME(s)	VOLTAGE(V)
0	2.7
60	2.6
150	2.5

Table 10: Charge and discharge results of 2.4V,1F

Transient Voltage drop(V)	Current (A)	Time to discharge to half the rated voltage(s)	Load resistance (Ω)
0.15	0.52	5	5



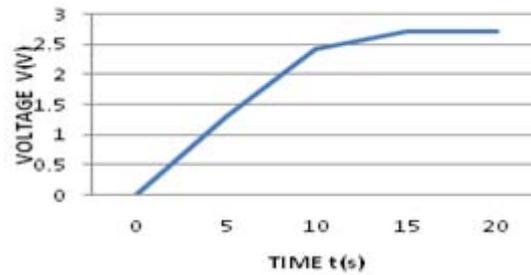


Figure 11: Charging and Discharging characteristics of Faradigm 2.4V, 1F.

Testing Of Faradigm 2.4V, 3.3F

The following graphs show the results obtained by testing the supercapacitor Faradigm 2.4V, 3.3F with a constant current charging of 0.89A and discharging through 5 ohms, 200W load resistance. Fig. 12 show the characteristics. Table 11 and 12 show the results.

Table 11 : Self discharge results of 2.4V,3.3F.

TIME(s)	VOLTAGE(V)
0	2.6
6.5	2.55
8.5	2.5

Table 12: Charge and discharge results of 2.4V,3.3F.

Transient Voltage drop(V)	Current(A)	Time to discharge to half the rated voltage(s)	Load resistance (Ω)
0.088	0.54	11	5

From the results, 2.4V, 3.3F supercapacitor's equivalent

$$C_{\text{CALC}} = 3.17\text{F}$$

$$\text{ESR} = 0.162\ \Omega$$

$$\text{EPR} = 1517.23\ \Omega$$

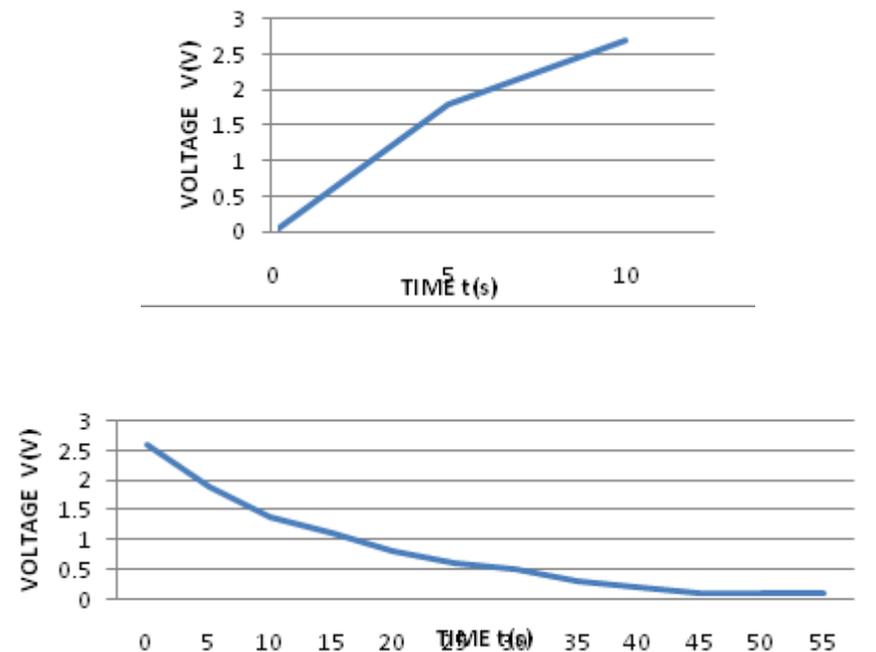


Figure 12: Charging and Discharging characteristics of 2.4V,3.3F

Testing of Ultracapacitor 100pp14 with Three Phase Inverter Circuit

A test set-up was developed to study the practical feasibility and implementation of supercapacitor with inverter which is connected to the grid. The test set-up was designed based on the supercapacitor '*KRANKINGTM ULTRACAPACITOR FD-100PP14*'. As the DC side voltage is 100 V, the AC grid side should have its maximum voltage less than 100 V. For a grid voltage of 65 V_{ph}, the peak value is 92 V (approx.). Three phase resistive load chosen is a balanced one with 14 ohms, 12A per phase. Switching frequency of the inverter is chosen as 5 kHz.

Inverter Design

IGBT CT60 with 900V and 60A rating is selected for the inverter. The switching frequency is chosen as 5 kHz. As the operating voltage is 65 V and current is 15 A maximum, no snubber circuit is required. IGBT requires negative pulses to turn off and so a gate drive circuit which gives positive and negative voltage is used.

Gate Drive Circuit

The gate drive circuit includes optocoupler, for isolation, and push-pull amplifier to produce both positive and negative pulses. Fig. 13 shows the IGBT gate drive circuit.

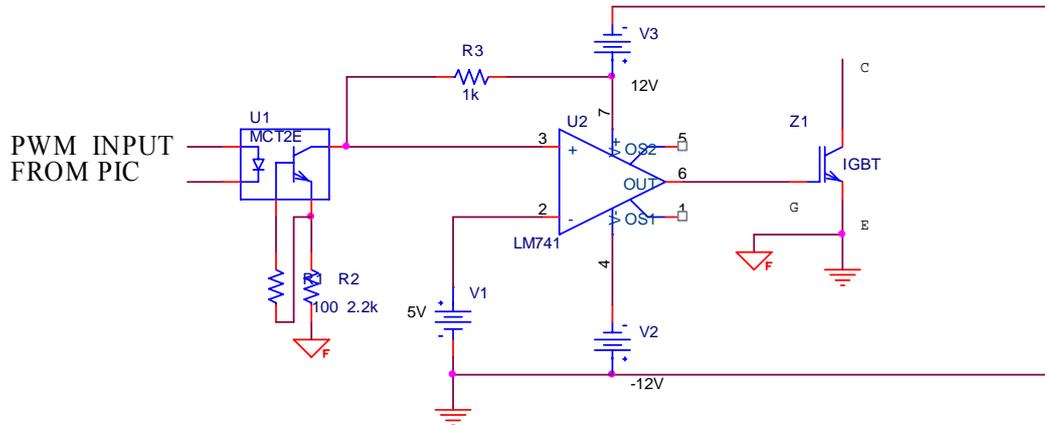


Figure 13: IGBT isolation and gate drive circuit.

Transducers

Voltage and current are measured using corresponding transducers. The transducer used for voltage sensing is LV 20-P and for current sensing is LA 25-P.

Bridge Rectifier with Voltage Regulator

The 230V AC supply is stepped down to 15V by a 230/15V transformer. The stepped down voltage is then rectified using a full wave rectifier designed using diodes 1N4007. The DC voltage from the rectifier is filtered using a 470 μ F capacitor. The filtered DC voltage is given to the voltage regulator ICs 7815, 7915 to give constant +15V, -15V DC output respectively. These voltages are required for driving the gate supply of the IGBT. Also 7805, 7812, 7912 ICs are used to regulate +5V, +12V, -12V respectively for the supply to PIC microcontroller, current and voltage transducers. Fig. 14 shows the circuit for bridge rectifier with voltage regulator.

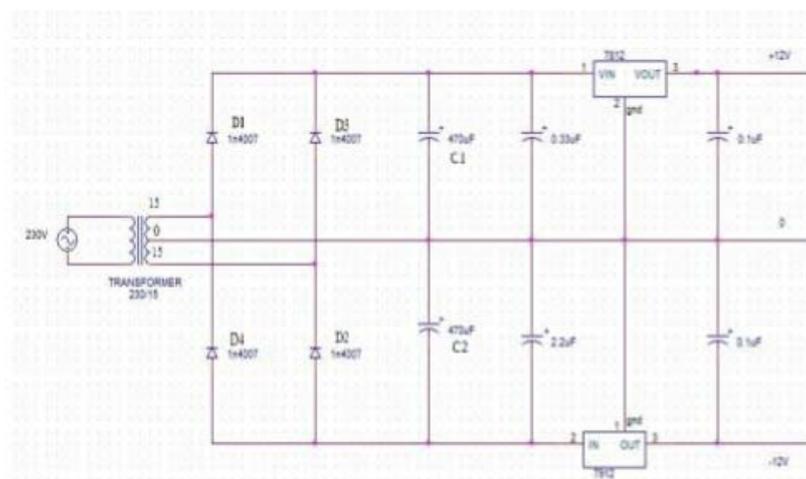


Figure 14: Bridge rectifier with voltage regulator.

Difference Amplifier

Difference amplifier is formed by combining the inverting and non-inverting amplifier configuration for getting the difference of two voltages which are multiplied by a constant. The two gain magnitudes are made equal for rejecting the common mode signals i.e. noises. The signals from Current transducer and Potential transducers, which can be easily affected by noises. So we go for Difference amplifier such that the actual signals can be retained. A zero crossing detector is used for detecting the zero crossings of AC signals. The inverters are to be switched on only at zero of the line current. Peak Detector is used to hold the peak value of the sine wave. During ADC operation in the microcontroller the peak value of the sine wave will be compared with its reference so the peak detector is used.

Microcontroller

PIC16F877a is a 40 pin high performance flash microcontroller with five input output ports and fifteen interrupts. It has 8kB program flash memory, 368 Bytes Registers as Data Memory, 256 Bytes of non-volatile EEPROM with eight A/D input channels. Three timer modules can be used for capture/compare/PWM/timer operation. There are two types of registers. All these registers are 8 bit registers so the maximum resolution will be $1/(2^8-1)$.

Coding for the control strategy is implemented in PIC16F877a microcontroller. As only one ADC is possible in this microcontroller, the digital conversion of the signals takes place sequentially. Once the digital signals are obtained, the reference current values are determined. These values are compared with the STATCOM currents. The resultant values are fed to a hysteresis controller to generate the gating controller signals, which is then fed to the gate drive circuit to generate gating signals to the inverter in STATCOM. Fig. 15 shows the working model of gate drive circuit controlled by PIC16F877A. Fig.16 and 17 show the circuit diagram and hardware set up of overall hardware circuit used for testing the super capacitor interfaced with the three phase inverter and grid.



Figure 15: Working model of gate drive circuit controlled by PIC16F877A.

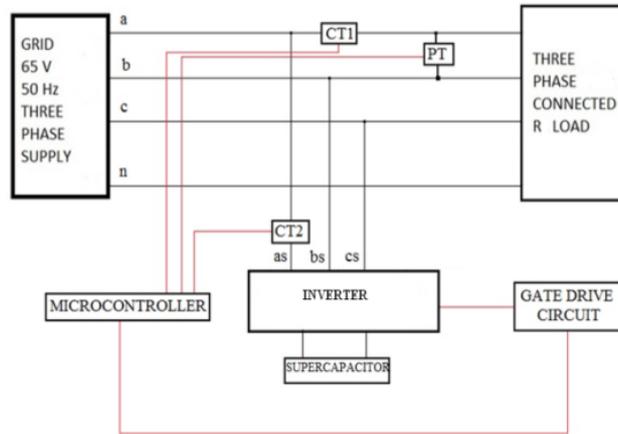


Figure 16: Overall circuit diagram.



Figure 17: Overall hardware circuit of 100PP14 super capacitor with grid connected three phase inverter.

Table 13 and 14 shows the results of hardware set up without and with super capacitor. Results show that grid is supplying full load power before the supercapacitor is included. After the supercapacitor is included, supercapacitor is partially supplying the load power apart from meeting the inverter losses.

Conclusion

Tests confirmed that super capacitors have series resistance in the range of milliohms and capacitance in the range of few farads. Results also show that supercapacitors can be used for many power quality applications where fast charging and discharging are needed. Self discharge tests showed that voltage drops due to leakage current causing power loss is not negligible. Supercapacitor 100PP14 was connected to the grid through fabricated three phase IGBT inverter and testing was carried out. Results show that supercapacitor is supplying real power to the load as well as supplying the switching and conduction losses of inverter. Table 15 shows the summary results of tested supercapacitors.

Table 13: Hardware results on load side without supercapacitor.

Voltage(V)	Current(A)	Power(W)
30	3	125
40	3.9	220
50	4.8	370

Table 14: Hardware results with supercapacitor.

Grid side			Inverter with Super capacitor side			Total power Consumed(W)
Voltage(V)	Current(A)	Power(W)	Voltage(V)	Current(A)	Power(W)	
30	2	100	35	1	70	170
40	2.8	170	45	1.2	100	270
50	3.4	300	55	1.4	140	440

Table 15: Summary of results.

Parameters	Faradigm 2.4V, 3.3F	Faradigm 2.4V, 1F	Kranksing 15PP1	Kranksing 15PP3	Kranksing 24PP30	Kranksing 100PP14
RATED VOLTAGE (V)	2.7	2.7	12	12	24	100
MAXIMUM VOLTAGE (V)	3	3	15	15	29	105
RATED DISCHARGE CURRENT (A)	4.4	0.74	150	300	2000	385
CAPACITANCE (F)	3.3	1.0	15	27	104	3.278
ENERGY STORED (kJ)	3.04	1.0	1.6	3.0	30	14
ESR (Ω)	0.288	0.162	0.192	0.192	0.0816	0.125
EPR (Ω)	3224.89	1517.23	1769.98	371.26	112.4	5928.16
WEIGHT	1.1 g	1.6 g	3 kg	5 kg	24.5 kg	8 kg

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