Supercapacitor based cost effective hybrid energy storage system with reduction in battery size for diesel generator cold cranking

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Article Info

Article history:

Received Aug 20, 2022
Revised Mar 8, 2023
Accepted Mar 12, 2023

Keywords:

Diesel-generator
HESS
Lead-acid
Microcontroller
Supercapacitor

ABSTRACT

The supercapacitor characteristic of high-power delivery coupled with very fast charge/discharge cycles find its use in hybrid energy storage systems. In this paper, the supercapacitor bank is integrated with small capacity lead-acid battery for the development of cost-effective hybrid energy storage system to crank vintage model of diesel-generator. The developed system uses microcontroller-based controls with active voltage balancing circuit with reliable cranking, enhanced battery life and reduced failures at low temperatures are the advantages of the developed system. The developed system resulted in battery size reduction by almost 80%, and thus, reduction in its replacement cost, besides devising a general formula for the sizing of supercapacitor bank for different diesel generators is an innovative outcome of the research study. The multiple cold cranking in a single charge of supercapacitor bank is another novelty, with the charging of supercapacitor bank from the available automobile battery is the added feature in the developed hybrid energy storage system. The developed system paves the ways for the reduced maintenance.

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1. INTRODUCTION

Batteries combine long duration high energy and short duration high power discharges with longer charging periods. Many electrical energy driven applications demand high power with frequent and rapid charge/discharge at high efficiency for critical loads, pulse loads, transportation systems, electric vehicles (EV), diesel engines, and power grids [1]. The supercapacitor (SC) in conjunction with battery plays an important role to form hybrid energy storage device which can meet combine demand of high energy and high power with reduction in battery size along with an enhancement of its cycle life as they will be relieved from the frequent high or pulse power discharges.

Batteries undergo thermally dependant slower electrochemical process during charge and discharge process; thus, the electrical behaviour of battery is non-linear [2]. The thermal runaway scenario that could result in a fire, especially in the case of Li-ion batteries, makes the batteries more catastrophic [3]. In pulse mode, only a small portion of the total energy is provided and removed, which is beneficial for the battery's thermal management. Miller and Burke [4], this difference becomes critical for fast charging and excessive charging leads to gassing which can cause an explosive atmosphere. Widely used lead-acid batteries are prone to shedding, dry out, acids stratification and surface charge which leads to decrease in useful life of the battery [5], particularly, in the case of infrequent operations and when batteries are kept in a completely drained condition or a very low state of charge (SOC) for an extended period. The lead-acid battery construction i.e., flooded or sealed, does not have influence on the lifetime, and it is associated to the shape of electrode [6]. Starting lead-acid batteries used for engine cranking are not meant for deep cycling since their plates are relatively thin with a large surface area for high current discharge. The discharge rate of the lead-acid battery reduces at low temperatures with fall in capacity at lowest temperatures and thus, cranking capacity is seriously impaired with peak efficiency dropping 65% at 0 ºC, and when capacity drops below discard level of 70%, the internal resistance increases by 20-30%. Also, to meet high-power requirements for the engine cranking at low temperatures, lead-acid batteries need to be greatly oversized. On the contrary, resistance of the supercapacitor changes little at -10 ºC to -15 ºC and increase 2-3 times at -40 ºC [7]. Thus, internal resistance of the storage system is crucial for the engine cold cranking capacity in addition to the resistance of cables, contacts, starter motor total resistance [8], [9]. However, lead-acid batteries are economical as compared to other types of batteries and therefore, widely used for vehicle and diesel-generator (DG) cranking applications. As compared to batteries, supercapacitor (SC) possesses unique properties-such as deep charge and discharge capability, high power density, very long cycle life, wide operating temperature range, maintenance free operation, and environmentally safe and its use for the short duration high power delivery in hybrid energy storage system (HESS) relieves battery from thermal management issues arising out of rapid high-power charge/discharge cycles. The supercapacitor-based hybrid system is capable of maintaining the lead-acid battery SOC at high limits, ranging from 90-95% with terminal voltage of 12 V [10]. A characteristic comparison between lead-acid battery and supercapacitor is given in Table 1.

Table 1. Lead-acid battery and supercapacitor characteristics

Parameter	Lead-acid battery	Supercapacitor
Charge time	5-7 hrs	0.3-30 sec
Discharge time	0.3-3 hrs	0.3-30 sec
Wh/Kg	10-100	1-10
Cycle life	<1,000	>100,000
W/Kg	<1,000	<10,000
Cycle efficiency	0.7-0.85	0.85-0.98
Working temperature	-20 ºC-60 ºC	-40 ºC-65 ºC

The direct battery-supercapacitor combination for the engine cranking in automotive engines resulted in the increased total number of cranking by the battery [11] and it is also reported that a 15-litre diesel-engine was attempted to start with open circuit voltage of around 11 V with 40% SOC of the battery but could not start the engine, but 64 KJ electrochemical capacitor when charged at 11 V from the same battery system, it started the engine four times at 0 ºC [12]. In power system also, the supercapacitors play crucial role for power quality, capacity enhancement of the micro-grid, and motor starting to reduce cost of starting devices [13], [14]. Even, in the case of large induction motors, starting and fluctuating loads causes serious effect of instability on the diesel-generator operation due to wide frequency variations [15]. In a DC microgrid, slow start-up dynamic response of DG is compensated by the supercapacitor to improve microgrid dynamic characteristics [16]. The supercapacitor-battery combination helps in reduction in the fuel consumption in hybrid electric vehicles (HEV) with improved battery voltage, and the reduction in emissions for better climate quality through minimized engine idling [17], [18]. The supercapacitor uses for the ‘infrequent’ cranking with lapse of days or weeks duration is possible due to its charge holding capability, and therefore, such characteristic is most suitable for ‘infrequent’ cranking applications such as diesel-generator units, military vehicles, private airplanes, and certain military applications. Thus, it is imperative to augment supercapacitor with battery through appropriate controllers to form cost-effective and efficient HESS for high power requirements in specific applications. This paper is organized as follows; section 1 focuses on the literature research, section 2 deals with proposed method and methodologies, section 3 give method adopted for the system development with hardware setup used in the research work and section 4 presents results obtained and findings from the experimental trials followed by concluding remarks in section 5.

2. PURPOSED METHOD

The infrequent use of DGs and field vehicles with long standby time has significant impact on the deterioration of lead-acid battery lifetime. The vintage diesel-generator (VDG) plants use lead-acid batteries of larger capacity and weight as compared to batteries used in today’s modern diesel-generators. The replacement cost for VDG is quite high and thus, their replacements may not be justifiable for standby operations. The cold temperature influences the engine and battery fluids and increases the viscosity, making it harder to start the engine. The lead-acid electrolyte also become more viscos in the cold climate and thus, increases the impedance, so discharge current is reduced. Thus, solely relying on the hot cranking amperes could be misleading for the selection of battery or design of SC bank capacity. The hybrid energy storage systems using supercapacitors gain advantage in low temperature areas, where battery SOC fails to crank diesel engines. It is reported that the lower battery size i.e., 5 Ah or 10 Ah, 12 V is used successfully to charge the supercapacitor bank of 6 cells (1,200 F and 2,000 F) for cranking 1,100 CC engine with reduction in starting time from 1.5 second with battery alone to 0.7 seconds for 400 A supplied by the hybrid system and 370 A supplied by the supercapacitor alone [19]. However, it is found from the literature research and manufacturer data that there is a research gap in employing cost-effective hybrid energy storage devices in the cranking application of DGs. The use of reduced battery capacity with appropriate control strategy and reduced cranking duration is proposed through economically viable alternative. The proposed HESS is aimed for the quick cold cranking of the 11.2 kVA 2-cylinder VDG with engine capacity of 1,560 CC. It is targeted that the proposed hybrid energy storage system design with supercapacitor bank is capable of multiple cold cranking in a single charge of around 80% SOC.

2.1. HESS controllers

In hybrid energy systems, the controllers are used for dynamic and frequent function of supercapacitor to supply very high power for short durations. A parallel connection of battery with supercapacitor without control circuit results in poor performance of the supercapacitor, and therefore, suitable converters, such as reversible buck-book converters between these storage devices are used in HEV for the full exploitation of supercapacitor power in dynamic mode [20], [21]. Also, combination of supercapacitors in parallel with battery through independent converters are also used for better overall control of high and energy delivery [22]. The semi-active controller is also used because of its rapid response to the supercapacitor voltages [23], [24]. The bi-directional converters are also reported for the dynamic controls and thus, slower aging of batteries operated in their narrow range of SOC during charge-discharge limits [25]–[27]. The dynamic buck-boost converter for efficient controls of voltages is shown in Figure 1 [28], [29].

Further, the series-parallel connected supercapacitor cells in HESS lead to voltage imbalance and hence internal discharges [30], and therefore, voltage balancing is necessary, particularly in dynamic controls. The voltage balancing methods i.e., passive balancing by using series/shunt resisters and active balancing by using solid state controllers are normally used. The accurate dynamic voltage balancing through individual cell have high efficiency as excess energy of the cell returns to the power supply and thus, it prevents premature ageing of supercapacitors [31]. A dedicated active auto-balancing using MOSFETs arrays integrated circuit shown in Figure 2 provides faster voltage balancing of the series cells with less complexity, and lower cost.

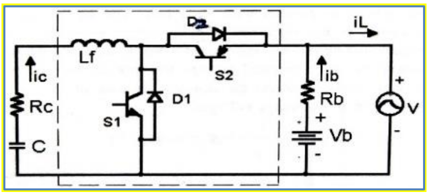

Figure 1. Buck-boost converter

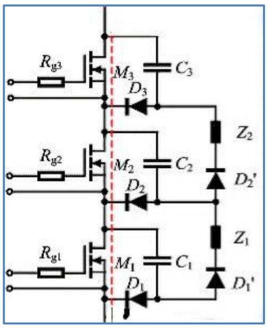

Figure 2. Supercapacitor voltage balancer circuit

However, for infrequent short duration high-power applications, such as cranking of DGs and military vehicles, the strategy of control can be different as it does not require dynamic controls during their operation but demands quick and reliable starting of the DGs and military vehicle at low temperatures. Therefore, it is proposed to incorporate microcontroller based digital controls along with active voltage balancing by MOSFETs arrays circuit for the efficient switching of the given storage device in the hybrid system. The proposed voltage balancing method, although non-essential, is aimed at achieving the longer retentivity of the supercapacitor SOC for infrequent use and to effect multiple cranking in a single charge.

2.2. Supercapacitor based hybrid model

The supercapacitors are governed by the characteristic similar to conventional capacitors; however, its charge storage mechanism is different, and thus, its performance characteristics are in between battery and capacitors. The nature of discharge characteristic of the supercapacitor is dictated by their circuit time constant, which is important for the maximum or pulse power delivery. It is evident from the Figure 3 that the discharge characteristic for supercapacitor bank is governed by the circuit series resistance (R_S) for the given SC bank equivalent capacitance (C_C) and voltage (V). A simplified battery-supercapacitor HESS model for the cranking of diesel-generator is shown in Figure 4, wherein input charging currents are shown by dotted arrows. In this model, the importance of diffusion resistance, surface capacitance and leakage resistance are neglected for pulse power delivery for cranking the vintage diesel-generator.

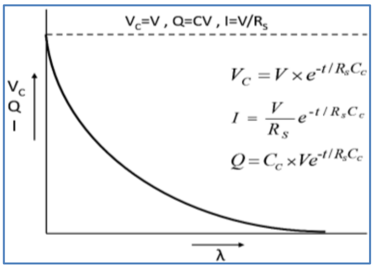

Figure 3. Discharge characteristic of capacitor

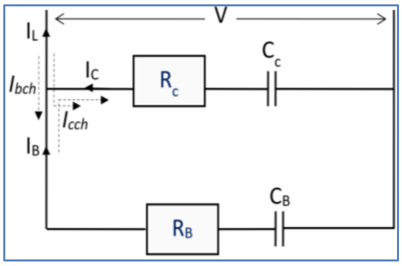

Figure 4. Battery-supercapacitor HESS (I_{bch} and I_{cch}-battery and SC charging current)

The maximum power (P_{max}) or maximum current (I_{max}) transfer by the supercapacitor bank is governed by the energy stored (E_C), SOC and internal resistance of the supercapacitor bank (R_C). The relationship governing the E_C, C_C and P_{max} is given by (1) to (4). The P_{max} given by (2) is on the basis of impedance matching and overestimates the power excessively. On the other hand, the P_{max} by (4) is based on 95% pulse efficiency (EF), which results in the usable maximum power being only $1/10^{th}$ of what it is given by (2), and therefore, does not yield a realistic value for most pulse power applications, especially, vehicle engine and diesel-generator cold cranking. The P_{max} given by (3) is recommended by the United States advance battery consortium (USABC) [17] and give realistic value for the practical purposes.

$$E_C = \frac{1}{2} C_C V^2 \quad (1)$$

$$P = \frac{V^2}{4R_{C_{max}}} \quad (2)$$

$$P = \frac{V^2}{8R_{C_{max}}} \quad (3)$$

$$P = \frac{9}{16} \frac{{V_o}^2}{R_{C\,max}} \quad (4)$$

Only 80% of the electrical energy is used when the supercapacitor bank discharges between V_{max} and V_{min}. Where V_{min} is 50% of V_{max} since, below this value, the electronic converter/controller efficiency rapidly decreases [17]. The nominal system voltage is restricted to 80% SOC, and therefore, $V=V_{max}$ and thus, an extended cycle life of the supercapacitors for the pulse power applications. Therefore, for $\Delta V=V_{max}-V_{min}$ with pulse power or maximum power duration of ΔT seconds, the relationship given by (5) hold good for accounting supercapacitor useable power and power lost in heat. Thus, by knowing the P_{max} or I_{peak} or I_{CCA} (cold cranking amperes), the estimation of C_C is given by (1) or (5) for given ΔV and ΔT. Normally, the rated voltage of the supercapacitor cell (V_{CELL}) is in the range of 2.5 to 3 V for different manufacturers. Based on the rated voltage of the supercapacitor cell, the rated system voltage of the supercapacitor bank is obtained by connecting number of cells in series (N_S) and is determined by the relationship, V_{RATED}=N_S V_{CELL}. The number of parallel paths of the SC series string is dictated by the selection of SC cell ratings. The dynamic for energy the starting period is given by (8), however, for the pulse power application its importance is lost, and therefore, more practical estimation of energy is done by (9). The value of C_C as obtained from (5) is used in (6) for the given choice of C_{CELL} with number of parallel paths (N_P). The equivalent resistance of the supercapacitor bank (R_C) is given by (6) for the selected cell. It is important to note that the choice of C_{CELL} ratings along with its internal resistance play a vital role in estimating the C_C by using (4).

$$\Delta V = I_{avg} \frac{\Delta T}{C_C} + I_{avg} \times R_C \tag{5}$$

$$C_C = \frac{N_P}{N_S} C_{CELL} \tag{6}$$

$$R_C = \frac{N_S}{N_P} R_{CELL} \tag{7}$$

$$E_{start} = \int_0^{\Delta T} v(t) \times i(t) dt \tag{8}$$

$$E_C = \frac{1}{2} C_C (V22_{min_{max}} \tag{9}$$

2.3. Diesel engine cranking circuit analysis

For the cranking of diesel engine, the fly wheel is revolved between 150 to 250 rpm depending on the engine capacity, design, temperature, age and hence, the current and time required for engine start. As start torque of diesel engine is much higher due to high compression ratio, therefore, larger CCA is needed. Increase in cranking speed improves starting performance at very low temperatures. The starting or cranking time normally falls in the range of approximately 1-2 second for a warm engine, to over 3-5 seconds for cold cranking due to increase in fuel viscosity and lower engine speed, and thus, starting get worse with instable combustion of fuel [32]. High power density or current density is a key requirement for cold cranking of the internal combustion engines for which lead-acid batteries are widely used to supply peak current to the starter motor for 3 to 5 second duration. High-capacity diesel engine starting normally needs extremely high current peak for around 250 ms, then reduced amperes at a reasonably stable voltage for 0.5 to 3 seconds [33]. This short duration peak current is governed by the starting circuit resistance and other parameters. There are six parameters which govern the performance characteristic of starter motor i.e., armature resistance, armature inductance, back emf, armature torque, movement of inertia and viscous friction [34]. The effect of armature inductance is lost for the transient power requirement in cranking. A d.c. series motor starter, which is characterised by low resistance with self-compensation feature of armature reaction, is a cost-effective choice as compared to the permanent magnet motors [35]. The reputed engine starter manufacturer (Bosch) provides 0.8 to 1.4 kW starter motor for engines up to 1,400 CC, 1.6 to 2.0 kW for utility vehicles, and 2.5 to 3.2 kW for light and medium size commercial vehicles with 12 V ratings. Therefore, it is also appropriate to consider starter motor rating to calculate initial stalled amperes for the estimation of the supercapacitor bank capacity to achieve multiple cranking. Normally, starter motor resistance is in the range of 0.02 to 0.05 ohm, and R_C is dependent on the R_{CELL} of the selected C_{CELL} rating. As per the manufacturers offering, the R_{CELL} value ranges from 0.025 to 0.006 ohm for C_{CELL} ratings from 50 F to 600 F. The CCA rating is the best yardstick for the estimation of supercapacitor ratings. However, peak starting current or P_{max} or E_C required for selected cranking duration can also be estimated from the starter motor ratings for C_C determination.

3. METHOD

Many industries and establishment worldwide, particularly in developing and poor countries, still use VDGs which are cranked by the large size lead-acid batteries. The outright replacement of such standby power plants needs large capital investments. Beside this, such units are also in operation at many remote places, where low temperature climatic conditions exist with intermittent or no grid power supplies. The HESS design for such diesel-generators is aimed for the comprehensive study and to overcome all plausible technical and operational challenges through cost-effective methodology with long operational time for the hybrid energy system. Therefore, keeping these considerations in mind, a vintage model (1987 KOIL make) of 11.2 kVA, 230 V capacity diesel-generator is selected for the implementation of the new supercapacitor-battery hybrid energy storage system for its efficient and reliable cold cranking. The selected VDG has on-board 1.4 kW, 12 V starting d.c. series motor, which is presently supplied by 12 V, 180 Ah lead-acid starting battery. Normally, the engine capacity for 10-12.5 kVA DG falls in the range of 1,500-1,600 CC as specified by the different manufacturers. The CCA of 362 A for 2-3 seconds is detected by the digital clamp-on ammeter which facilitated one of the primary estimates for selected VDG. The second estimate for the CCA is also determined from the starter motor ratings. Therefore, considering the most appropriate value for the CCA, the estimation of the supercapacitor bank equivalent capacitance, designing of the microcontroller-based control circuit with devised algorithm, associated switching devices, protections and voltage equalizer circuit is worked out for the new system. The proposed system encompasses pre-charging operation of supercapacitor bank through battery or on-board alternator for the multiple cold cranking in 80% SOC of the supercapacitor bank.

3.1. Estimation of supercapacitor bank capacity

The estimation of the supercapacitor bank to supply targeted pulse power or current is based on the cold cranking, which is defined at -18 ^oC before the voltage dropping to 7.2 V for 12 V battery with current lasting for 30 seconds, whereas the normal cranking current is defined at 0 ^oC. The maximum power or current occurs at a voltage of 75-80% of open circuit voltage and is expected to remove only small amount of the energy stored in the supercapacitor. Therefore, once the electrical resistance of the cranking circuit is known, its power or peak current capability follows directly. For the VDG engine under consideration, a large amount of cranking current is needed owing to its mechanical designs and sizes of the old components involved in the mechanism and therefore, the capacity of supercapacitor bank needs to be estimated based on the maximum current delivery.

The cold cranking test with 12 V, 180 Ah battery alone recorded the initial peak starting current of 362 ampers at battery open circuit voltage of 12.8 V, and this current then dropped down to 208 ampers in less than a second with battery voltage recovering to 10.2 V at the end of the 3-second cranking duration. Therefore, an average energy requirement during the cranking period is 2.223 KJ which needs 0.2375 Ah. However, based on the initial peak starting or stalled starter motor current, the estimated C_C from (5) is 241 farads.

Also, from the starter ratings, the calculated stalled current is 375 ampers for circuit resistance of 0.032 ohm. It is observed that the initial starting current at the beginning of the cranking is around 2-times the rated input current of 1.4 kW, 12 V starter motor with standard 60% efficiency. Therefore, from the initial stalled current, the estimated value of C_C from (5) is 253 farads.

The first step is to estimate rated system voltage with consideration of engine starter voltage rating. Accordingly, V_{CELL} and N_S is selected so that around 80% SOC of rated system voltage is just below the maximum open circuit voltage of the battery. Therefore, for N_S=6 and V_{CELL}=2.7 V, rated system voltage is 16.2 V and the nominal system voltage is V=12.96 V at 80% SOC, but the maximum nominal system voltage for the bank is considered at 12.5 V (77% SOC) being dictated by the open circuit battery voltage of 12.7 to 13 V. Now, (3) gives P_{max}=4.069 kW for R_C=0.0048 ohm, and thus, corresponding maximum energy of 12.2 KJ provides an estimate for C_C=209 farads from (9). Thus, from the above three estimates of C_C, an average CC is taken as 234 farads, which is rounded off to 250 F to determine C_{CELL} and N_P. The number of parallel paths (N_P) are estimated as from (6) and give N_P=4 for the selected C_{CELL}=400 F with R_{CELL}=0.0032 ohm from the specification offerings by the manufacturers. The R_C from (7) comes out to be R_C=0.0048 ohm for N_P=4. Therefore, if C_C and N_S are calculated for the given voltage or SOC, then it is the choice for the selection of C_{CELL} among offered specifications from different supercapacitor brands, and hence required N_P. However, the selection of C_{CELL} should result in overall cost effectiveness of the system with lesser circuit complications and thus, improved controllability and reliability. However, the choice of C_{CELL} is dictated by the wide scale availability of the SC cells as the reputed brand available in the market are handful.

From the above design calculations and manufacturers data analysis, a generalized innovative formula has been devised to provide C_C values for different capacity DGs. The findings resulted in an approximate factor C_X=150 F/kW for 4-cylinder engines and C_X=170 F/kW for 2-cylinder engines with 12 V electrical starting motor. The Sc bank designed based on this factor is capable of at least five to six successive cold cranking of given diesel engine in a single full charge of the SC bank. Therefore, the devised generalised formula to estimate C_C for electrical cranking is given by (10), which has been verified for the different DG set ratings with their starting motor specifications and concluded that the formula is adoptable. Figure 5 gives estimation characteristic to select C_C for the standard cranking amperes (SCA) at operating temperature of 21 ^oC for the given engine capacity. Similarly, in (10) is also verified for the different kW input power ratings of the d.c. starter motor, and thus C_C values can easily be obtained from Figure 6 for the cold cranking amperes (CCA).

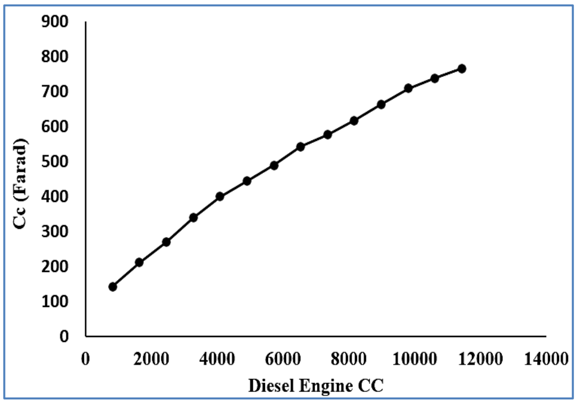

Figure 5. C_C for SCA of engine CC (at 21 ºC)

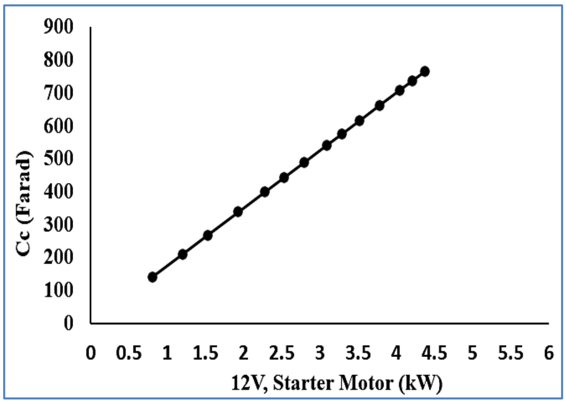

Figure 6. C_C for CCA from starter motor rating

$$C_C = C_x \times P_{SM(KW)} \tag{10}$$

Were, C_X=150 F/kW for 4-cylinder engine and 170 F/kW for 2-cylinder engine.
$P_{SM(KW)}$ =Electrical starter motor power rating at 12 V d.c. supply.

3.2. Control circuit

Method of control for the hybrid energy storage system model is dictated by the given application and cost. The ATmega8 is a low-power microcontroller architecture which executes powerful instructions in a single clock cycle. The ATmega8 approaches 1 MIPS per MHz, allowing the system to optimize power consumption with higher processing speed. In the microcontroller based developed control circuit, 400 ampere solenoid relay is used in the cranking circuit to supply cranking current to the starter motor and 100 ampere solenoid relay is used for charging/discharging mode operation of the battery. The supercapacitor voltage balancing function is integrated in the developed HESS control circuit by using MOSFET SAB IC (ALD810025). Block schematic diagram with different functional block of the new scheme for the cranking of VDG is shown in Figure 7. The hardware layout with different components of the developed HESS is shown in Figure 8, wherein necessary protections, display to read storage device status etc have been incorporated.

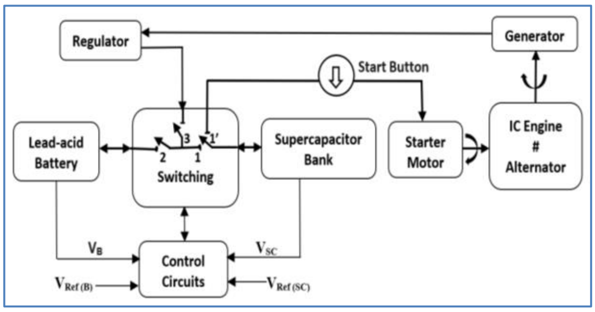

Figure 7. Block schematic of HESS controls

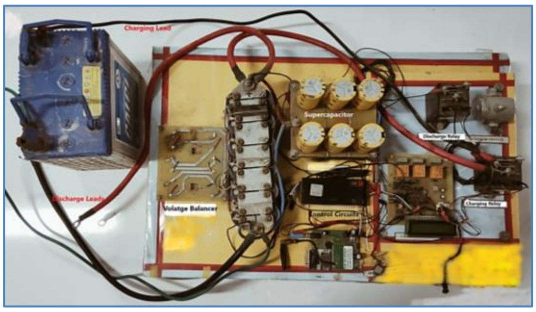

Figure 8. Hardware layout of developed HESS

An algorithm for the design of supercapacitor bank design for hybrid energy storage system is shown in Figure 9. The HESS control algorithm with different equalities and inequalities needed as standard checks for efficient switching actions and voltage controls is shown in Figure 10, wherein battery failure ends the process prematurely and therefore, supercapacitor bank needs to be charged by an auxiliary small battery just up to cranking SOC and thereafter, on board alternator can charge the bank and battery for future cranking. Such situations are rare and taken care by the control circuit with voltage balancer for longer retentivity of SOC for SC bank.

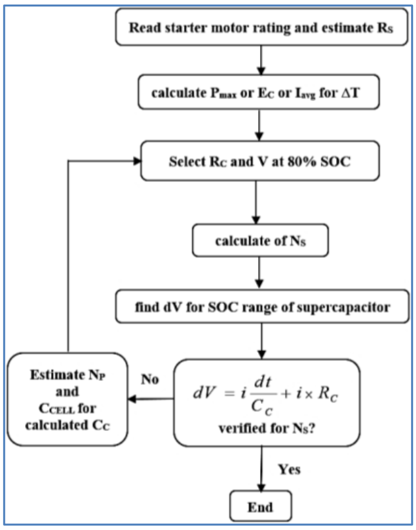

Figure 9. Algorithm for SC bank design

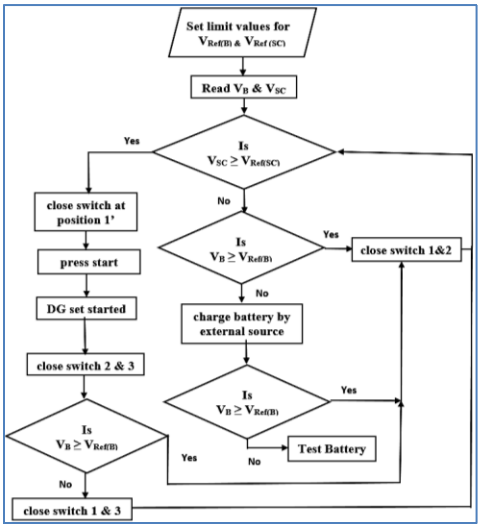

Figure 10. Algorithm for developed HESS controls

4. RESULTS AND DISCUSSION

The developed new HESS unit is tested successfully for the 11.2 kVA vintage type diesel-generator to crank it six times in a single charge of supercapacitor bank. The developed HESS module has also been tested successfully for the cranking of diesel-generators up to 20 kVA or 25 HP. The maximum charging current drawn by the SC bank from the battery was 95 A, which is considerably less than the current supplied by the battery alone to crank engine. Therefore, there is a reduction in stress on the lead-acid battery and thus, improved battery life. It is important to bring out that the successive cranking in a single charge of SC bank is sometimes essential for the frequent cranking and, in the absence of desired battery SOC at low temperatures. It has been the innovative idea to incorporate multiple charging modes for the SC bank through on-board alternator or small capacity lead-acid battery. Even readily available small capacity automobile battery can also be used for the charging of supercapacitor bank deployed in multiple DGs at the same plant. Further, because of the voltage balancing integrated circuit, the charge retentivity of the supercapacitor bank has increased substantially, and thus, cold cranking of the DG after a prolonged gap in between its operation is possible.

4.1. Charging and discharging characteristic of SC

The charging current variations of supercapacitor bank is shown in Figure 11, wherein, the maximum charging current (I_{chg}) is 95 A and the SC bank takes maximum 9 seconds to charge SC bank from minimum 7 V to 12.5 V, in fact it takes 3 to 4 seconds to charge from 80% SOC to 100% SOC to reach at nominal system voltage. The state of SC bank voltage with discharge current is also shown in Figure 12, wherein, the voltage dropped from its maximum value at 12.5 V to 10 V for six successful cold cranking with discharge current (I_{dch}) ranging from 410 A to 240 A.

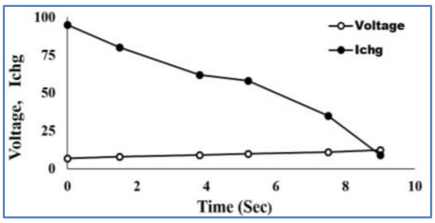

Figure 11. Supercapacitor charging

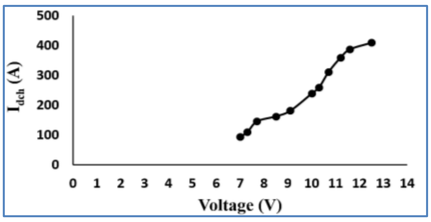

Figure 12. Supercapacitor discharging

Another finding is that the HESS is capable of cold cranking in less than 2-seconds with six successful number of cranking up to 10 V (80% SOC). The lead-acid battery capacity is optimized from 180 Ah to 35 Ah for charging the supercapacitor bank and the battery capacity can further be optimized to 20 Ah as the total energy required for the successive six cold cranking is only 3 to 4 Wh as per the design calculations. Therefore, it can be concluded that, if battery is relieved from supplying the cranking/starting pulse current then considerable reduction in the size and capacity of the lead-acid battery can be achieved. Even sharing of peak current by battery-SC hybrid system also results in overall economy through reduction in the number of SCs.

4.2. Characteristic formula to select SC bank capacity

An innovative aspect of the research study is about the development of generalized relationship for the sizing of the SC bank capacity based on diesel engine capacity (CC), kVA rating and the starter motor rating. The devised formula given by (10) is based on the design calculations for different specifications of the manufacturers. A Figure 13 give requirement of the SC bank equivalent capacitance (Cc) for diesel engine CC capacity for the CCA. It is seen from the Figure 13 that; the Cc increases somewhat linearly for lower engine capacities but later it is fairly constant for the given range of engine CC with sudden increase after 4,500 CC. Figure 14 give Cc necessary for the different kVA rating of the diesel engine generators and seen that the C_C requirement varies almost linearly for lower kVA capacities but increases rapidly beyond 50 kVA. However, proportionate increase in C_C for higher kVAs is less 50 kVA due to increased engine cylinders with turbo charging features of DGs.

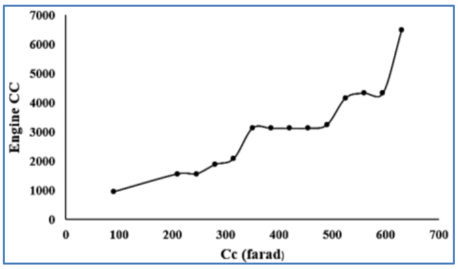

Figure 13. C_C for CCA of engine CC

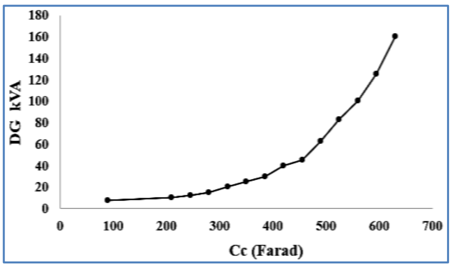

Figure 14. C_C for CCA of DG kVA rating

4.3. Cost analysis

The selected low-capacity battery is intended to charge supercapacitor bank only, and the capacity of the battery can further be optimized for this developed HESS. The available automotive 12 V, 35 Ah battery; in place of 12 V, 180 Ah battery, is used for the cranking of 11.2 kVA vintage diesel-generator by on-board 1.4 kW, 12 V d.c. series motor. The present market cost of the 12 V, 180 Ah lead-acid battery is around $200. The normal cycle life of lead-acid battery is maximum 1,000 cycles, whereas the normal cycle life of the supercapacitor is 100,000 cycles. Therefore, an enormous saving in terms of the replacement cost the batteries can be estimated. At the rate of present market cost of the lead-acid battery, the total replacement cost of the batteries could be $20,000 during the given cycle life of the supercapacitors. The expected life of the supercapacitors is further enhanced as the maximum SOC is restricted to 80% i.e., 12.5 V as against rated volage of 16.2 V. The present market cost of 400 F powerstor (eaton make) supercapacitor is $12 for single piece and the overall cost of the developed HESS system is approximately $950, which will reduce further during its mass production. Thus, the pay-back period for the cost of developed cranking HESS is five years, which is negligible in comparison to the total replacement cost of batteries during the cycle life of the supercapacitors.

5. CONCLUSION

In the developed smart hybrid energy storage system for the cranking of vintage diesel-generator, the main innovation lies in the reduction of lead-acid battery capacity by almost 80% because of the SC bank integration with the lead-acid battery for DG cranking. The hybrid energy storage system with its microprocessor-based control system is capable of several cold cranking in a single charge of 80% SOC of the supercapacitor is an added innovation of this research study. Battery less charging of supercapacitors through on-board alternator is also an added feature in the developed algorithm. Further, the developed HESS module is capable of cranking higher capacity diesel-generators, where starter motors up to 2 kW ratings are deployed to crank diesel-engine. The use of voltage equalizer circuit in the system control circuit resulted in the longer charge retentivity of the supercapacitor, and thus, most suitable for the infrequent operations of diesel-generators at low temperatures. The cost saving through reduced battery capacity in the long term is substantial, besides the amenability of the developed system for the solar charging while operating the diesel-generators in the remote areas. A generalised formula devised for the supercapacitor bank sizing for the different diesel-engine capacities or for given starter motor rating is also a main innovative research outcome, and the formula may be treated as a ready reckoner to select SC bank capacity.

ACKNOWLEDGEMENT

The authors are very appreciative to the late Prof (Dr.) D. G. Bharadwaj for his guidance and encouragement in conducting this research. The management of the Bharti Vidyapeeth College of Engineering Pune is also acknowledged by the authors for providing the necessary infrastructure for the research project. The College of Military Engineering (CME) Pune, which provided funds for the establishment of the laboratory equipment and instrumentation to carry out research, is also thanked by the authors.

REFERENCES

[1] M. Farhadi and O. Mohammed, "Energy storage technologies for high-power applications," *IEEE Transactions on Industry Applications*, vol. 52, no. 3, pp. 1953–1962, May 2016, doi: 10.1109/TIA.2015.2511096.

[2] H. Dai and X. Chang, "A study on lead acid battery and ultra-capacitor hybrid energy storage system for hybrid city bus," in *Proceedings - 2010 International Conference on Optoelectronics and Image Processing, ICOIP 2010*, Nov. 2010, vol. 1, pp. 154–159, doi: 10.1109/ICOIP.2010.321.

[3] A. Burke and M. Miller, "Performance characteristics of lithium-ion batteries of various chemistries for plug-in hybrid vehicles," *24th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition 2009, EVS 24*, vol. 2, pp. 816–828, 2009.

[4] J. R. Miller and A. F. Burke, "Electrochemical capacitors: Challenges and opportunities for real-world applications," *Electrochemical Society Interface*, vol. 17, no. 1, pp. 53–57, Mar. 2008, doi: 10.1149/2.f08081if.

[5] A. Singh and P. B. Karandikar, "Lead-acid battery for HEV using fuzzy controller and ultracapacitor," in *2016 - Biennial International Conference on Power and Energy Systems: Towards Sustainable Energy, PESTSE 2016*, Jan. 2016, pp. 1–5, doi: 10.1109/PESTSE.2016.7516443.

[6] E. M. Laadissi, J. Khalfi, F. Belhora, C. Ennawaoui, and A. E. Ballouti, "Aging study of a lead-acid storage bank in a multi-source hybrid system," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 20, no. 3, pp. 1109–1117, Dec. 2020, doi: 10.11591/ijeecs.v20.i3.pp1109-1117.

[7] H. Liu, Z. Wang, J. Cheng, and D. Maly, "Improvement on the cold cranking capacity of commercial vehicle by using supercapacitor and lead-acid battery hybrid," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 3, pp. 1097–1105, Mar. 2009, doi: 10.1109/TVT.2008.929220.

[8] H. Liu, D. Maly, and Z. Wang, "Supercapacitor and lead-acid battery hybrid and improved diesel engine cold cranking," in *IET Conference Publications*, 2008, no. 538 CP, pp. 199–203, doi: 10.1049/cp:20080511.

[9] H. Liu, Z. Wang, S. Qiao, and Y. Liu, "Improvement of engine cold start capability using supercapacitor and lead-acid battery hybrid," in *Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC*, Feb. 2008, pp. 668–675, doi: 10.1109/APEC.2008.4522793.

[10] M. J. Lencwe, S. P. Chowdhury, and T. O. Olwal, "A multi-stage approach to a hybrid lead acid battery and supercapacitor system for transport vehicles," *Energies*, vol. 11, no. 11, p. 2888, Oct. 2018, doi: 10.3390/en11112888.

[11] M. A. M. Mahmudi and A. A. Gazwi, "Battery/supercapacitor combinations for supplying vehicle electrical and electronic loads," *International Journal of Electronics and Electrical Engineering*, pp. 153–162, 2014, doi: 10.12720/ijeee.2.2.153-162.

[12] Ong, Wee, and R. H. Johnston, "Electrochemical capacitors and their potential application to heavy duty vehicles," *SAE transactions*, 2000, 802-807, doi: 10.4271/2000-01-3495.

[13] X. B. Yang, H. M. Li, Z. Jiang, H. Wang, and Z. D. Yin, "Review on application of hybrid energy storage based on ultracapacitor," *Applied Mechanics and Materials*, vol. 341–342, pp. 1299–1302, Jul. 2013, doi: 10.4028/www.scientific.net/AMM.341-342.1299.

[14] C. R. Arunkumar, U. B. Manthati, and S. Punna, "Supercapacitor-based transient power supply for DC microgrid applications," *Electrical Engineering*, vol. 104, no. 2, pp. 463–472, Apr. 2022, doi: 10.1007/s00202-021-01312-7.

[15] G. Wei, S. Sun, and J. Liu, "Influence of motor starting on the operating characteristics of diesel generator sets," in *2016 4th International Conference on Machinery, Materials and Information Technology Applications*, 2016, doi: 10.2991/icmmita-16.2016.21.

[16] C. Yin, M. Sechilariu, and F. Locment, "Diesel generator slow start-up compensation by supercapacitor for DC microgrid power balancing," in *2016 IEEE International Energy Conference, ENERGYCON 2016*, Apr. 2016, pp. 1–6, doi: 10.1109/ENERGYCON.2016.7514058.

[17] F. Béguin and E. Frackowiak, *Supercapacitors: Materials, Systems, and Applications*. Wiley, 2013.

[18] W. F. Infante, A. F. Khan, N. J. C. Libatique, G. L. Tangonan, and S. N. Y. Uy, "Performance evaluation of series hybrid and pure electric vehicles using lead-acid batteries and supercapacitors," in *IEEE Region 10 Annual International Conference, Proceedings/TENCON*, Nov. 2012, pp. 1–5, doi: 10.1109/TENCON.2012.6412224.

[19] E. Jankowska *et al.*, "Hybrid energy storage based on ultracapacitor and lead acid battery: Case study," in *Advances in Intelligent Systems and Computing*, vol. 743, 2018, pp. 339–349.

[20] B. T. P. Singh, B. B. Phaneendra, and K. Suresh, "Extensive review on supercapacitor cell voltage balancing," *E3S Web of Conferences*, vol. 87, p. 01010, Feb. 2019, doi: 10.1051/e3sconf/20198701010.

[21] A. A. Gazwi, "Application of supercapacitors to automotive applications," *International Journal of Computer Science and Electronics Engineering*, vol. 1, no. 2, pp. 307–311, 2013.

[22] I. N. Jiya, N. Gurusinghe, and R. Gouws, "Hybridisation of battery, supercapacitor and hybrid capacitor for load applications with high crest factors: A case study of electric vehicles," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 16, no. 2, pp. 614–622, Nov. 2019, doi: 10.11591/ijeecs.v16.i2.pp614-622.

[23] C. Zheng *et al.*, "A hybrid energy storage system for an electric vehicle and its effectiveness validation," *International Journal of Precision Engineering and Manufacturing - Green Technology*, vol. 8, no. 6, pp. 1739–1754, Nov. 2021, doi: 10.1007/s40684-020-00304-5.

[24] J. Rocabert, R. Capo-Misut, R. S. Munoz-Aguilar, J. I. Candela, and P. Rodriguez, "Control of energy storage system integrating electrochemical batteries and supercapacitors for grid-connected applications," *IEEE Transactions on Industry Applications*, vol. 55, no. 2, pp. 1853–1862, Mar. 2019, doi: 10.1109/TIA.2018.2873534.

[25] Ammaiyappan, B. Sankar, and S. Ramalingam. "Design and Development of Bidirectional DC-DC Converters Using Battery/Supercapacitor for Electric Vehicle Applications. " *Electric Vehicles and the Future of Energy Efficient Transportation*, pp. 36-55, 2021.

[26] R. A. S. Pena, A. Hijazi, P. Venet, and F. Errigo, “Balancing supercapacitor voltages in modular bidirectional DC-DC converter circuits,” *IEEE Transactions on Power Electronics*, vol. 37, no. 1, pp. 137–149, Jan. 2022, doi: 10.1109/TPEL.2021.3093767.
[27] X. Luo, J. V. Barreras, C. L. Chambon, B. Wu, and E. Batzelis, “Hybridizing lead–acid batteries with supercapacitors: A methodology,” *Energies*, vol. 14, no. 2, p. 507, Jan. 2021, doi: 10.3390/en14020507.
[28] S. Pay and Y. Baghzouz, “Effectiveness of battery-supercapacitor combination in electric vehicles,” in *2003 IEEE Bologna PowerTech - Conference Proceedings*, 2003, vol. 3, pp. 728–733, doi: 10.1109/PTC.2003.1304472.
[29] A. M. Al-Modaffer, A. A. Chlaihawi, and H. A. Wahhab, “Non-isolated multiple input multilevel output DC-DC converter for hybrid power system,” *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 19, no. 2, pp. 635–643, Aug. 2020, doi: 10.11591/ijeecs.v19.i2.pp635-643.
[30] Y. Qu, J. Zhu, J. Hu, and B. Holliday, “Overview of supercapacitor cell voltage balancing methods for an electric vehicle,” in *2013 IEEE ECCE Asia Downunder - 5th IEEE Annual International Energy Conversion Congress and Exhibition, IEEE ECCE Asia 2013*, Jun. 2013, pp. 810–814, doi: 10.1109/ECCE-Asia.2013.6579196.
[31] Y. Kozhushko, T. Ryzhakova, O. Bondarenko, and Z. Stević, “Supercapacitor battery charger with voltage equilizing,” *Zbornik Međunarodne konferencije o obnovljivim izvorima električne energije–MKOIEE*, vol. 5, no. 1, pp. 127-134, Oct. 2017, doi: 10.24094/mkoiee.017.1.5.127.
[32] J. Zhou, J. Du, Y. Yuan, and D. Zhang, “Analysis on low temperature cold starting performance of Parallel Hybrid Electric Vehicle with ultra-capacitor,” *Applied Mechanics and Materials*, vol. 43, pp. 119–122, Dec. 2011, doi: 10.4028/www.scientific.net/AMM.43.119.
[33] R. Vishnurameshkumar, A. Kingsly, P. Karthikeyan, R. Muthukumaran, and B. Saran, “Starter motor control system,” *Int. J. Innovative Science, Engg & Technology*, vol. 2, no. October 2015, pp. 515–520, 2016.
[34] M. N. Abdullah, M. K. M. Desa, E. A. Bakar, and M. N. Akhtar, “Experimental and numerical studies for parameters identification of direct current motor,” *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 27, no. 2, pp. 592–600, Aug. 2022, doi: 10.11591/ijeecs.v27.i2.pp592-600.
[35] K. S. Mohammad and A. S. Jaber, “Comparison of electric motors used in electric vehicle propulsion system,” *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 27, no. 1, pp. 11–19, Jul. 2022, doi: 10.11591/ijeecs.v27.i1.pp11-19.

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