Starting of Locomotive Diesel Engines Using Electrochemical Capacitors

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INTRODUCTION

Electrochemical capacitors are getting more and more widespread in various spheres of application from small-sized electronic gadgets and communications facilities to large power supply systems with stored energy of megajoules.

Comprehensive fundamental researches and studies of electrochemical capacitors consumers qualities (1) contributed to wide acceptance of these products on a world market. Unique output power and service life rating determined application of such capacitors in powerful processes and for providing high reliability during operation. This type of power sources successfully competes with storage batteries in a number of spheres of application. Depending on stored energy, a capacitor is usually applied with a battery or instead of it.

Applied researches conducted in the beginning – mid 90s promoted development of the whole family of capacitors for starting of internal combustion engines (2, 3), which are successfully applied for starting road vehicles: motor cars, trucks, buses, etc.

In the following article adjusting possibility of capacitors sets for starting heavy locomotives engines (more than 1000 h.p.) is described, test data are shown and advantages of new starting devices and their economic efficiency of application are demonstrated.

It should be noted, that combined starting systems battery + capacitor are successfully applied for railway transport for more than 10 years, gradually forcing out traditionally used starting system based on batteries only.

1.PRE-REQUIREMENTS AND PECULIARITIES OF LOCOMOTIVE STARTING.

Starting of large diesel engines differs greatly from starting engines of small combustion volume (motor cars, trucks, etc). This difference lies in heavier weight of the moving parts: crankshaft + pistons and also in higher resistance to the piston motion in cylinder. Diesel engine efficiency is determined by this resistance – the higher the rate of compression, that is cylinder pressure, the higher its efficiency.

At starting of traditional low-powered engine, starter battery, is being discharged on the load of electric machine-starter, runs the main engine shaft up to starting frequency. After a certain number of working strokes of the crankshaft all starting operations are realized: fuel suction, mixture formation, compression and ignition.

While starting of locomotive diesel engine, starter battery is working initially for hydraulic pumps operation, which create pressure and suspend engine shaft before starting. In cold period of time preheating of oil in hydraulic system and other operations for engine heating are fulfilled. As a rule, the time of prestarting preparations is about 30 – 60 seconds and to the moment of engine starting the battery has already spent some part of its capacity. Besides, prestarting preparation and starting function, board batteries for locomotive provide functioning of board automatic equipment and air compressors, feeding car brake systems when the engine is not operating.

In operating condition when locomotive has often to stop shutting down the engine (due to ecological restrictions at passenger terminals), the power of board alternator is not enough to maintain the normal level of the board battery state of charge (~ 70%). Very often cases of battery capacity reduction to 30% of nominal occur. In such cases the internal resistance of the board battery is increased, the starting current is decreased and the cranking time of the engine shaft rotation before stable starting is increased. This situation greatly reduces the reliability of locomotive operation, sometimes breaking down its starting. Frequent and deep discharges may cause board battery failure, especially of lead-acid batteries. Exploiting companies often face with the dilemma: either not to shut down the engine during stops and thus wasting fuel during idle engine running or to increase the adjusting capacity of the battery and the board alternator power.

Summarizing all the above stated, we may note two main moments:

- cyclogram of locomotive engine starting differs greatly from that of road vehicles;

- board locomotive battery is more loaded than that of the road vehicle;

Here exist two wide-spread operating modes for electrochemical capacitors installed in equipment by application spheres. The first is to keep the capacitors in operating circuit in uncharged state. In this case the capacitor is charged just before using and after being discharged on the operating load it is disconnected from the charging circuit till the next turning on. The advantage of this kind of operation lies in long service life of the capacitor, because in the time intervals between connections its voltage is close to “zero”. All the processes on the electrodes causing aging are as if “freezed” in this state. But there is operation disadvantage in this method – one needs time for the full charging of the capacitor.

The second mode of operation – floating regime reveals the highest readiness for immediate discharge, but the service life of the capacitor set is lower than in the first case and special measures to equalize voltages of the high-voltage circuit are needed.

Availability of the preparation period before starting of the locomotive diesel in principle admits of applying the first algorithm and in this case stable continuous capacitor charging from the board battery with no current overloading is possible.

2. BATTERY STARTING. CURRENT / VOLTAGE PROFILE

There exist 3 electrochemical systems mainly used in starter batteries for diesel locomotive starting. They comprise lead-acid, nickel-cadmium and nickel-iron batteries.

Comparative data of some locomotive batteries are shown in Table 1.

Table 1.

Electrochemical system	Battery, Voltage, V	Capacity (5-hour discharge), A· h	Starting parameters		Specific power, W/Ah
			Maximum discharge current, A	Battery voltage at maximum current, V	
1. Lead-acid	96	450	2400	48	256
2. Nickel-iron	64	550	2200	37	148
3. Nickel-cadmium	96	160	2700	46	776

For lead-acid and nickel-cadmium batteries mainly the rule “5 C” is used. This means, that battery capacity is chosen at a rate of 1/5 of maximum value of peak current. Thus, if peak current during starting is 2000 – 2200 A, then nominal battery capacity would be 400 – 500 Ah. For cell design of these two battery types relatively thick electrodes (more than 3 mm) and free electrolyte volume are used. But ESR is rather high and in starting mode voltage drops up to 0,5 of nominal value.

For nickel – cadmium batteries the rule “10 – 15 C” is used. Their design provides for thin electrodes, ensuring lower ESR of battery cells in comparison with lead-acid and nickel – iron batteries.

Temperature range of starter batteries operation is wide enough: from - 45°C up to + 55°C of ambient temperature. That is why all locomotive batteries are of non-sealed (vented) design, otherwise it is impossible to ensure stable temperature condition when charging battery consisting of sealed cells, with the exception of “thermal runaway”. That increases operation expenses due to necessity of regular maintenance of vented cells. Current overload at the initial moment of starting leads to electrolyte loss during operation. Current overload for lead-acid batteries accelerates swelling up of active material of positive electrodes. For nickel-iron and nickel-cadmium batteries with cells of “pocket-type” electrode design it intensifies washing out of electrode material powder through lamella holes (“pocket”). These processes often result in internal shunting of electrodes in the cell block and premature battery failure.

Historically two standards of locomotive board voltage were determined – the old one of 64 Volts and modern – of 96 Volts. For 96 V level the lead-acid battery contains 48 cells and the nickel-cadmium battery – 72 cells. Multicell series circuit with components, disposed in different temperature patterns (edge – center), also prevents from principle sealing of board batteries.

Service life of board starter batteries is also over a wide range: from 1 to 5 years. Critical zones of operation are regions with cold and hot climate. Within the above mentioned range of service life the more long-term operation is maintained by the regular battery servicing on the shed stands, including replacement of the failed cells with new ones.

Some words about economic aspect of electrochemical systems application. Capital cost for purchasing of new board batteries are increased according to the row:

Lead-Acid $<$ Nickel–Iron $\ll$ Nickel-Cadmium.

As a rule, for the same locomotive type nickel-cadmium battery price is 3 times higher than the lead-acid battery price.

On the other hand, operation expenses are decreased according to this electrochemical system row:

Lead-Acid $\approx$ Nickel-Iron $>$ Nickel-Cadmium.

Let's analyze typical cyclogram of locomotive diesel starting (Fig. 1). Engine power is 3000 h.p. Type of battery used: nickel-iron 550 Ah, voltage – 64 V. Battery state fully charged (charge level ≈ 100%), ambient temperature +26°C.

Analysis of curves on Fig. 1 shows, that even under favorable starting conditions voltage drop in fully charged battery was 40% at the initial moment, starting current ≈ 1930 A. Diesel was stable started in 8,3 sec.

Fig. 2 demonstrates change of power, taken out from the battery during diesel cranking. It is evident, that maximum discharge power runs into ≈ 70 kW and is kept down to about 40…50 kW during 2 sec Total energy amount, taken out from the battery during 3 sec – 150 kJ, during 2 sec – 104 kJ.

For comparison let's analyze change of battery power during diesel cranking at 35% state of charge of the board battery (Fig. 3) in the course of 3 sec. One can see, that maximum discharge power at the peak does not exceed 25 kW, energy delivered during 3 sec is 67 kJ (Fig. 4).

In the course of cranking, voltage was reduced from 55 V to 20 V by the 16^{th} sec and starting was not fulfilled. The battery charge level of 35% is an extreme case, but nevertheless it often takes place, especially in winter.

Statistic analysis of starting reliability reveals, that starting guarantee drops abruptly when the state of charge of board battery is decreased. The range of stable starting is 70 – 100% of charge level, while the real operating range is 50 – 80%. Analyzing the graphs of Fig.1- 4 one can note, that for reliable starting of locomotives diesel with power of 3000 h.p. it is necessary to have a battery, capable to generate 100 – 120 kW peak power, taking into consideration operating at low temperature. In such case the board battery state of charge needs rather rigid control.

3. ADJUSTING THE SUPERCAPACITOR TO LOCOMOTIVE ARCHITECTURE.

Electrochemical capacitors possess higher, by 1-2 orders of magnitude, specific power than starter batteries. That is why they may be effectively used on locomotive board for realizing the most powerful processes - cranking of engine shaft at the initial moment of starting.

There exists a great number of technical embodiments of capacitors in starting systems. But in most cases the capacitor set is parallel connected to the board battery through the control circuit. As it was already mentioned in Section 1 of this paper it is possible easy to fulfill the algorithm: “charging-starting-disconnection” for capacitor operation due to engine preparation before starting.

Schematic view of the usually used scheme of capacitor connection to the starting circuit is shown in Fig.6.

Scheme of operation.

During preparation before starting capacitor set C is charged from Battery B through Thyristor VS, opened by a command, and through current –limiting Resistor R for reducing of battery current load.

Discharge on the electric machine load, that is diesel starting proper, takes place simultaneously for the battery and capacitor through Diode VD when the contacts of the starting circuit K are closed.

After starting capacitor C is removed from the circuit by closing Thyristor VS.

Energy store of the capacitor set may vary in a wide range depending on engine power and operating conditions. Let’s analyze practical test concerning starting of 3000 h.p. diesel (4), description of its starting from 550 Ah battery was mentioned in Section 2.

Basing on data of the delivered energy at the initial seconds of starting, one can determine capacitor energy store within the range of 90…180 kJ.

There was analyzed the most unfavorable case, when board battery state of charge was only 35% and the minimum capacitor energy store was ≈ 90 kJ. (The set ESR ≈ 10 mOhm).

Let’s analyze oscillogram at the beginning of starting, as it is shown in Fig. 7. It is evident, that discharged battery is unable to generate initial starting current for this diesel type (≈ 2000 A), only 610 A. Whereas the capacitor set easily runs into 1400 A current and total with weak battery current normal shaft rotation at the beginning of starting becomes possible.

Advantages of capacitors even with the minimum energy store for this diesel type over batteries are clearly manifested at the 1 second of starting, which is evident from the power profiles in Fig.8.

From graphs of released energy versus starting time (Fig.9) it is clear, that the capacitor has advantages initially during 1,8 sec, that is at the moment of maximum energy demand. And only in going to long stationary rotation the battery delivers more energy than the capacitor.

It should be noted, that in this test the normal starting have been realized at the 10^{th} second, the board battery state of charge being only 35%.

Let’s consider another case of capacitor application for locomotive engine starting (5):

- decreased diesel power:1200 h.p. instead of 3000 h.p.;
- increased energy store of the capacitor set – 144 kJ instead of 90 kJ;
- critical state of the board battery 100 V, 450 Ah, but charge level is only 30%;
- unfavorable starting conditions – ambient temperature of +2°C.

First engine cranking without starting from the battery separately and from the set battery + capacitor up to automatic switching off of starting relay were carried out.

The current/voltage profile (Fig. 10) demonstrates significant voltage drop – 54% of nominal and rather low pulse current – 876 A, while the one of 1300 – 1500 A is needed.

Power profile of battery discharge at the initial period of cranking shows the peak value ≈ 43 kW (Fig. 11) and the delivered energy value (Fig.12) runs into 43 kJ for 1,2 sec and 49 kJ for 1,4 sec. Total cranking time is 2 sec.

Parallel connected capacitor set of 144 kJ, 15 mOhm, 96 V was charged from this battery during 30 sec and the same cranking was carried out. The current/voltage profile (Fig.13) demonstrates less voltage drop – 34% and normal pulse current on the starter – 1413 A, which is the sum of the battery current – 378 A and the capacitor current –1035 A.

Thus, the starter battery at the initial moment of starting was discharged by the current less than “1 C”.

The power profile of the initial cranking period (Fig.14) shows almost three fold excess of the capacitor power over the battery within the time period of ≈ 100 milliseconds.

Total peak power of the capacitor and the battery reaches 94 kW, compared with 43 kW in case of the battery alone. As far as delivered energy is concerned, Fig.15 demonstrates, that the capacitor “outruns” the battery within the interval of 1,4 sec, delivering more energy to the starter. In such case the battery delivers only 21 kJ, that is more than twice less, than by cranking only from the battery. Total energy output from the system capacitor-battery is 47 kJ for 1,2 sec – a little bit more, than energy output only from the battery.

But total cranking time with the combined system was increased more than twice and presented 4,5 sec, instead of 2sec as with the battery alone.

Further testing supposed starting implementation and it was noted by this that:

- starting from the battery only (state of charge was 30%) – was not realized;

- starting from the system capacitor + battery – was stable realized in 0,5 sec;
- starting from the capacitor set only was stable realized in 0,5 sec.

The latest experiments show, that for the determined ratio 1200 h.p./144 kJ, using the battery is not necessary for warranted starting of the locomotive diesel.

Further investigation led to the development and mass production of the unified starting system with technical data, shown in Table 2.

Table 2.

Parameter		**Value**
	System Type	SPD 2200/64(96)
1	Power of engines being started	1000…3200h.p.
2	Nominal operating voltage	96/64 V
3	Maximum operating voltage	110 V
4	Nominal discharge current	3500 A
5	Maximum discharge current	10000 A
6	Total energy store	135 kJ
7	Capacity	26/58 F
8	ESR	< 0,010 Ohm
9	Insulation resistance	> 5 MOhm
10	Service life (cycling)	> 100000
11	Mass	< 120 kg
12	Dimensions	426 x 420 x 545 mm

The system consists of 3 capacitors connected parallel-series depending upon board system voltage, charging device from the board battery, control circuit.

4. ADVANTAGES, RELIABILITY, EFFICIENCY.

Comparing the results of testing and long-term operation of starting systems with batteries only or with combined systems battery + capacitor, we can come to the following conclusions:

- the capacitor set in couple with board battery takes upon all power functions during maximum starting energy demand (initial seconds of engine starting); its power several times exceeds the starter board battery power;
- capacitor energy output to the starter is higher than that of the battery at the initial starting period;

- state of charge of the battery does not affect the starting characteristics;
- the battery is not subjected to large current loading during starting, its operating conditions become more moderate;
- it was noted, that starting energy was used efficiently. 43 kJ from the battery during 1,2 sec rotate the engine shaft only for 2 sec; starting is not realized; 47 kJ during initial 1,2 sec from the system battery + capacitor rotate the shaft for 4,5 sec. In operating conditions the engine is started for 0,5 sec.

Now the advantages of the combined system battery + capacitor over common starting system on the basis of the battery only should be noted:

- warranted starting of the locomotive diesel at any state of the board battery, including operation in cold climate, is ensured;
- starting is possible without board battery or with a battery of several times reduced capacity;
- cycling life of electrochemical capacitors represents hundreds of thousands of charge - discharge cycles. Depth of discharge of the board battery during operation in a couple with capacitor is several times less, whereas its service life is increased. It was noted, that the capacitor set + battery system is operating at least twice longer;
- board battery maintenance and repair expenses are cut down approximately in half.

It should be noted, that the capacitor set pillar is a compact unit and the fact, that capacitors are sealed and maintenance-free makes it possible to arrange the capacitor set in almost inaccessible places of the locomotive compartments. Besides, the above mentioned advantages of the combined system prove its high reliability during operation and practical independence of many exposure factors.

Aspects of economic efficiency of capacitor application for locomotive starting systems are based on the proper choice of the capacitor energy store, taking into consideration the specific character of locomotive operation. Thus, shunting locomotives it is preferably to have higher energy store, than for mainline locomotives, because of the many more stops in the “start-stop” mode for shunting locomotives. It also concerns the commuter trains which often stop.

Efficiency aspects of combined system application may be conventionally subdivided into long-term and short-term.

Long-term economy is determined on the base of:

- increasing of system service life;
- reducing of maintenance expenses.

It is well-known, that maintained batteries during service life need expenses equal to or even exceeding the initial battery cost. It is easy to calculate economy, which may be obtained when the service life is increased twice and maintenance expenses are three times reduced.

Short-term economy is calculated on the base of:

- possibility to apply board battery with 2-3 times reduced capacity and accordingly reduced cost;
- reducing of fuel consumption when capacitor set is applied additionally to standard board battery with large capacity. It provides possibility often to stop the engine and to guarantee its further starting. Besides, increasing of engine operating resource is possible.

Reverting to fuel economy defined during years of combined systems operation, that the capacitor set fully compensates the capital expenses for 2- 4 months from the beginning, taking into consideration fuel cost and operation intensity.

There exist some disadvantage of the combined system though having no influence upon reliability and economy. It is availability current-limiting resistor in the charging circuit of capacitor sets for reducing of battery current inrush at the initial moment. Low efficiency of charging process, heat release into the surrounding compartment. The best way out is to apply pulse or DC/DC converters. But their price at present time is economically unacceptable.

CONCLUSION

1. Electrochemical capacitors can be easily adjusted into starting locomotive system for operation in any charge algorithm. At the same time specific parameters of capacitors sets do not have influence on it.
2. Electrochemical capacitors are effectively applied in starting locomotive systems, guaranteeing engine starting with no dependence on state of charge of board battery and weather condition, increasing reliability of vehicles operation.
3. Application of electrochemical capacitors is economically effective by prolonging service life of starting system, by reducing expenses on board battery maintenance, by economizing fuel and by increasing engine shelf life.

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4. Test Protocol “Estimation of Efficiency of Use the Capacitor Set in Starting System of Locomotive 2 TE 1OM”, ELIT Co/Kursk Locomotive Depot, July, 1995.

5. Test Protocol “Estimation of Efficiency of Use the Capacitor Set in Starting System of Diesel-Train DR- 1A”, ELIT Co/Gomel Locomotive Depot, March, 1996

Exhibits: Fig. 1 – Fig. 15

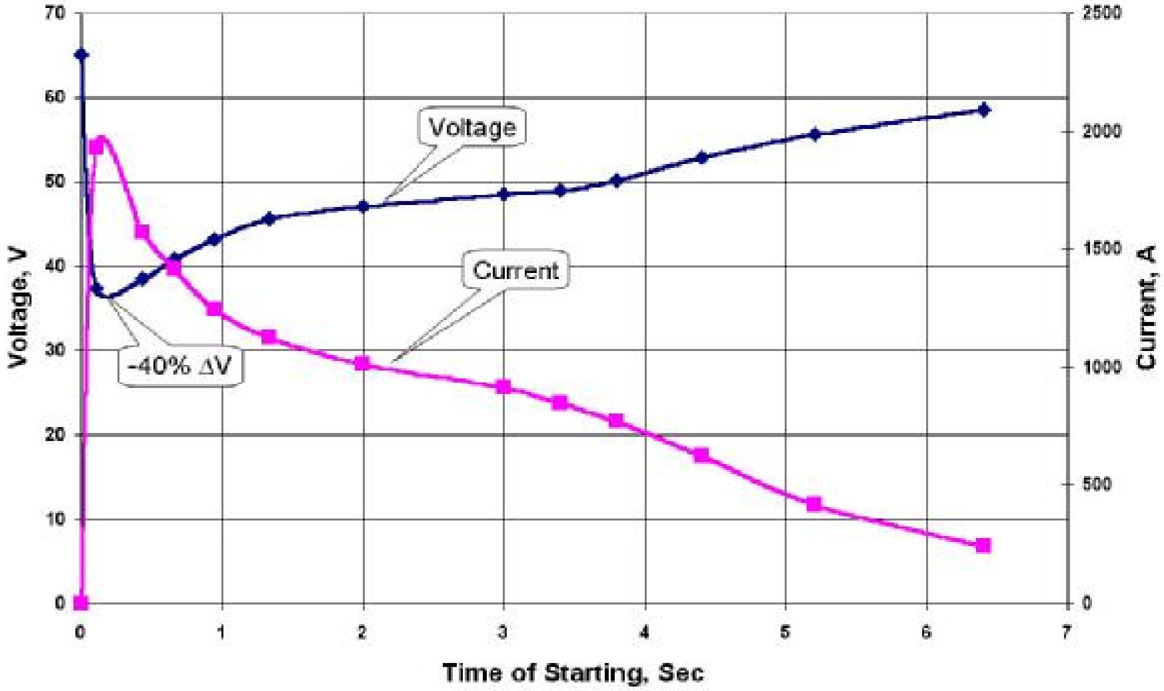

Figure 1. Current/Voltage Profile. Battery Only, State of Charge > 100 %;
Engine 3000 h.p. Temp. + 26ºC.
Rotation Time to Start – 8,3 sec.

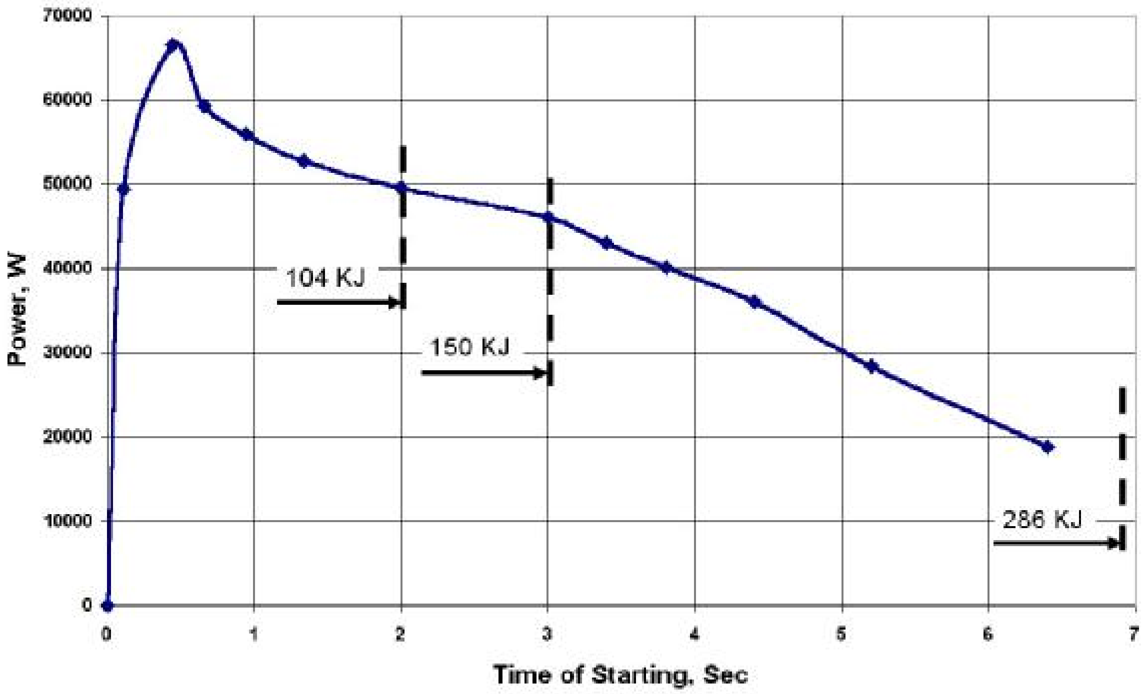

Figure 2. Power Profile For Starting Discharge of Board Battery.
State of Charge > 100%; Engine 3000 h.p.; Temp. + 26ºC.

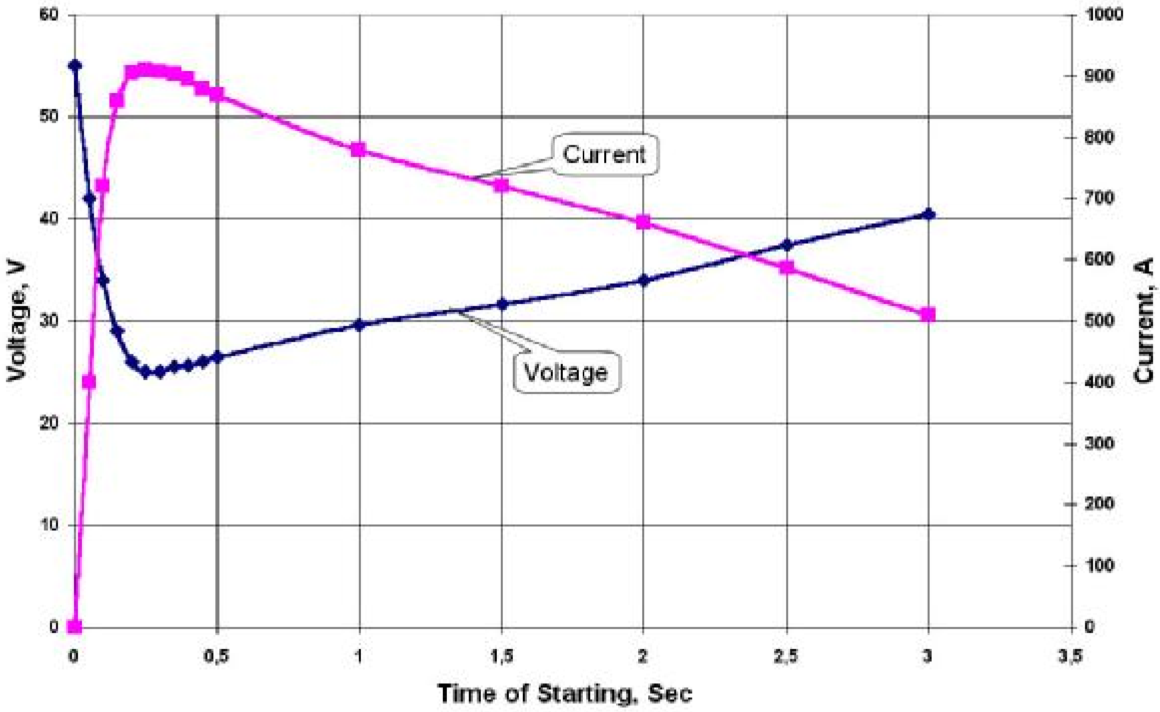

Figure 3. Current/Voltage Profile of Initial Time of Starting.
Battery State of Charge - 35%; Engine - 3000 h.p.

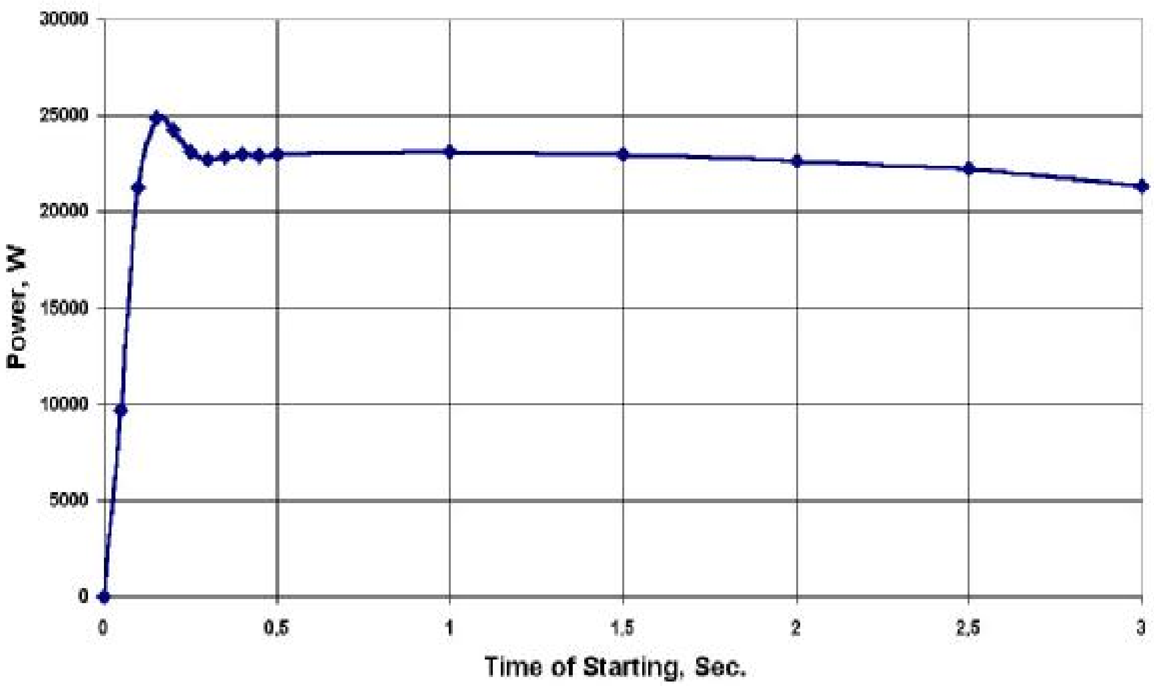

Figure 4. Power Profile For Starting Discharge of Board Battery.
State of Charge - 35%; Engine 3000 h.p.

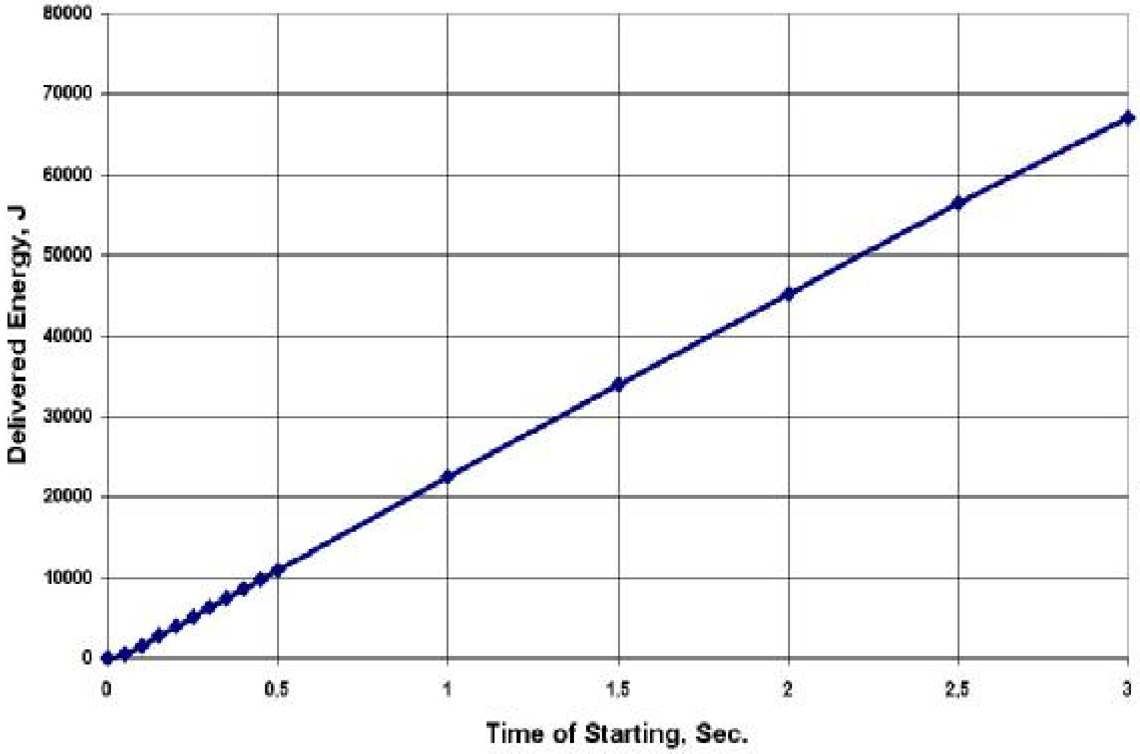

Figure 5. Delivered energy of Board Battery in Starting Discharge.
State of Charge - 35%; Engine 3000 h.p.

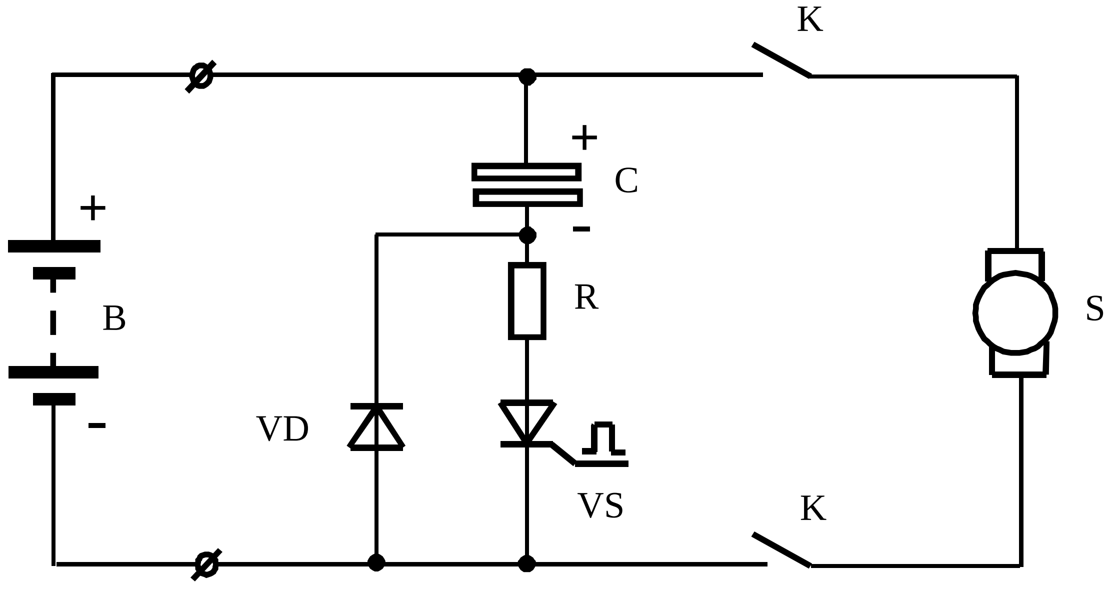

Figure 6. Adjusting the Supercapacitor to Locomotive Starting Circuit.
B - Board Battery; C - Capacitor Set; S - Electric Machine Starter;
VD - Diode; VS - Thyristor; R - Current Limiting Resistor;
K - Starting Contactors.

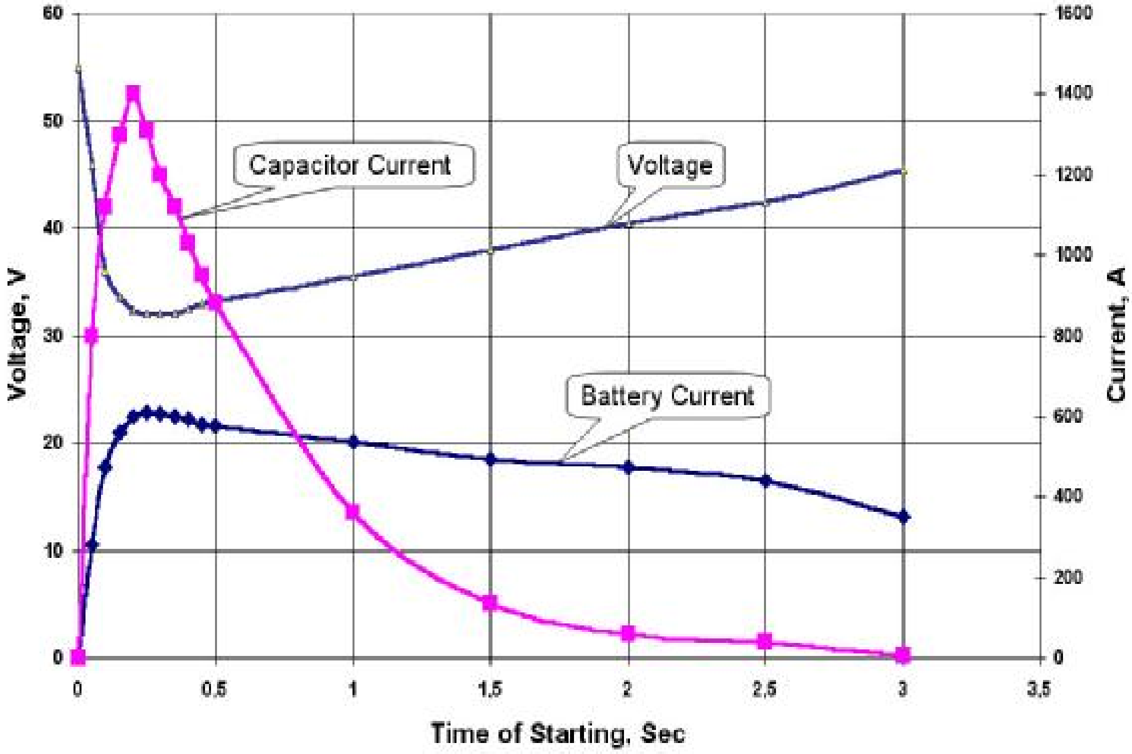

Figure 7. Current/Voltage Profile of Initial Part of Starting.
Battery 35% State of Charge; Capacitor ~ 90 kj; Engine 3000 h.p.

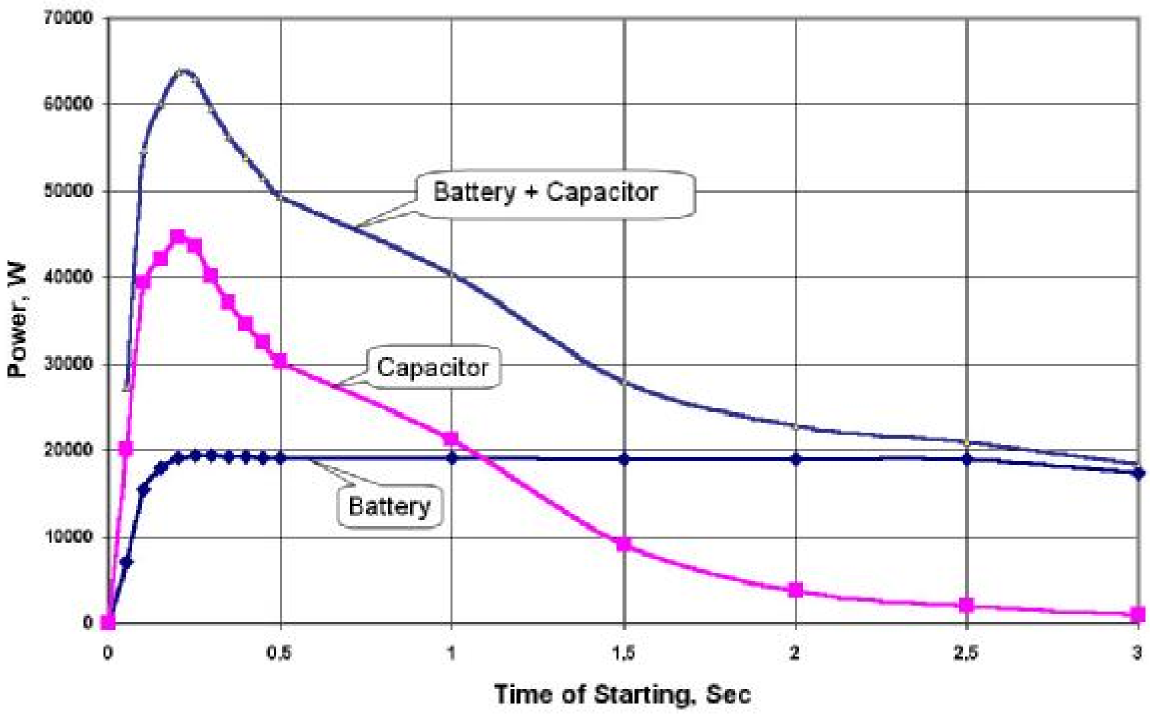

Figure 8. Power Profile of Initial Time of Starting, Battery + Capacitor
Battery State of Charge 35%; Capacitor 90 kj; Engine 3000 h.p.

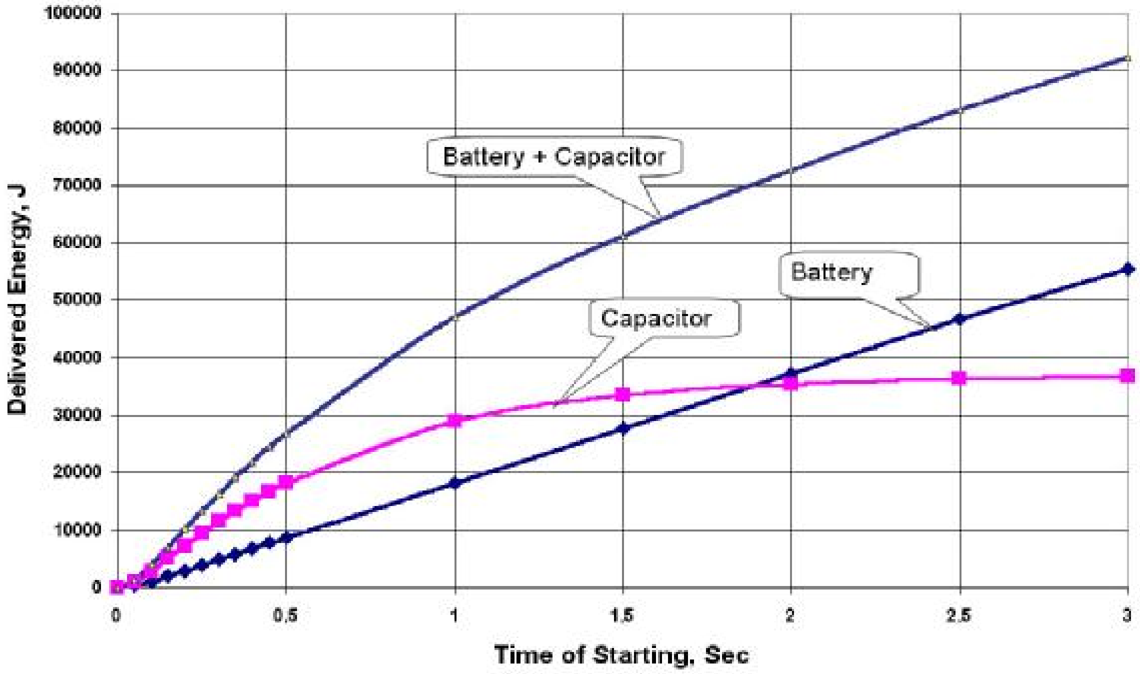

Figure 9. Delivered Energy in Starting Discharge, Battery + Capacitor.
Battery State of Charge - 35%; Capacitor - 90 kj; Engine 3000 h.p.

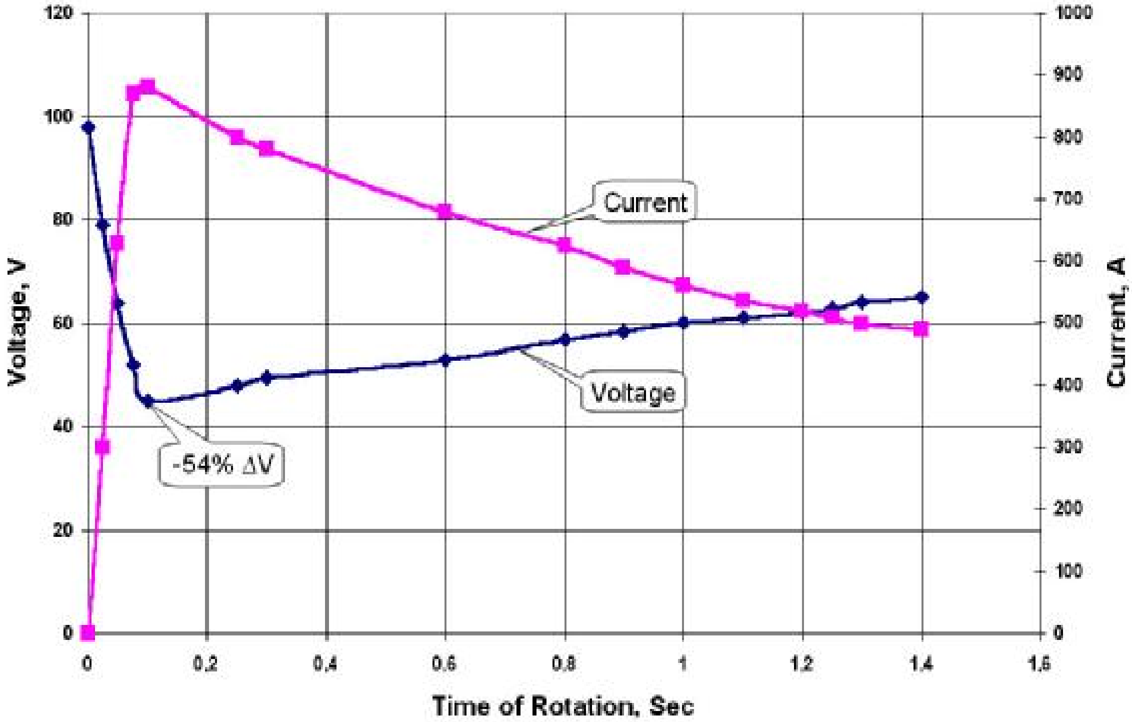

Figure 10. Current/Voltage Profile. Initial Period of Rotation.
Battery Only, 450 Ah, State of Charge ~ 30 %
Engine 1200 h.p. Temp. + 2ºC.

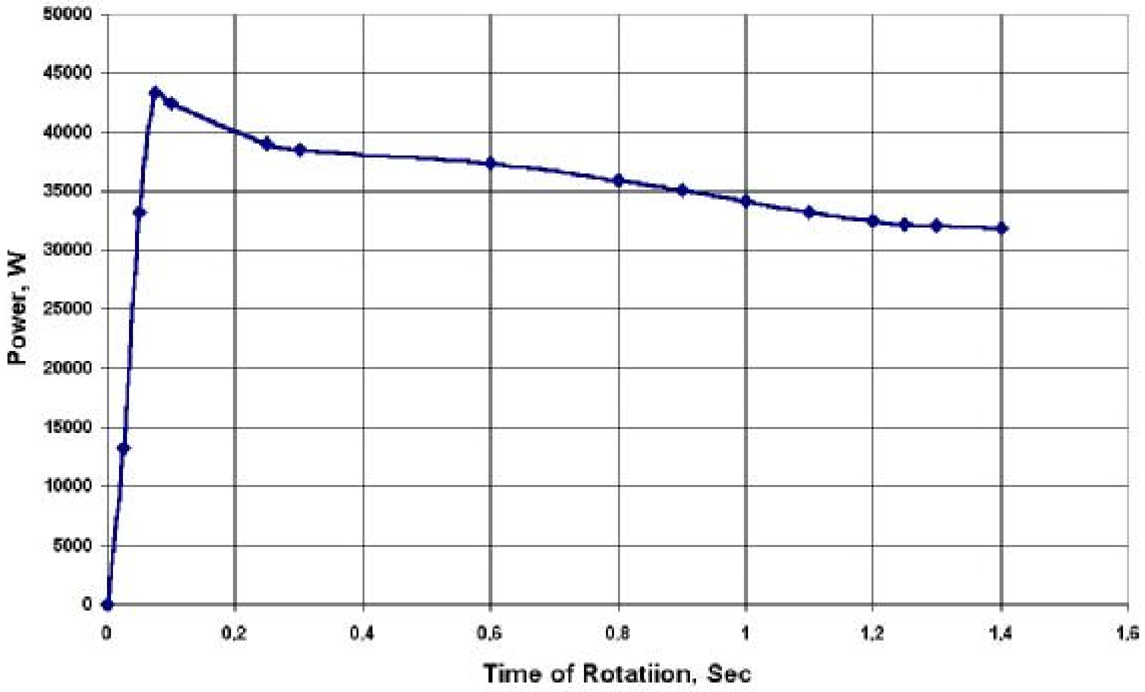

Figure 11. Power Profile, Initial Period of Rotation.
Battery Only, 450 Ah, 96 V, State of Charge ~ 30%.
Engine 1200 h.p. Temp. + 2ºC.

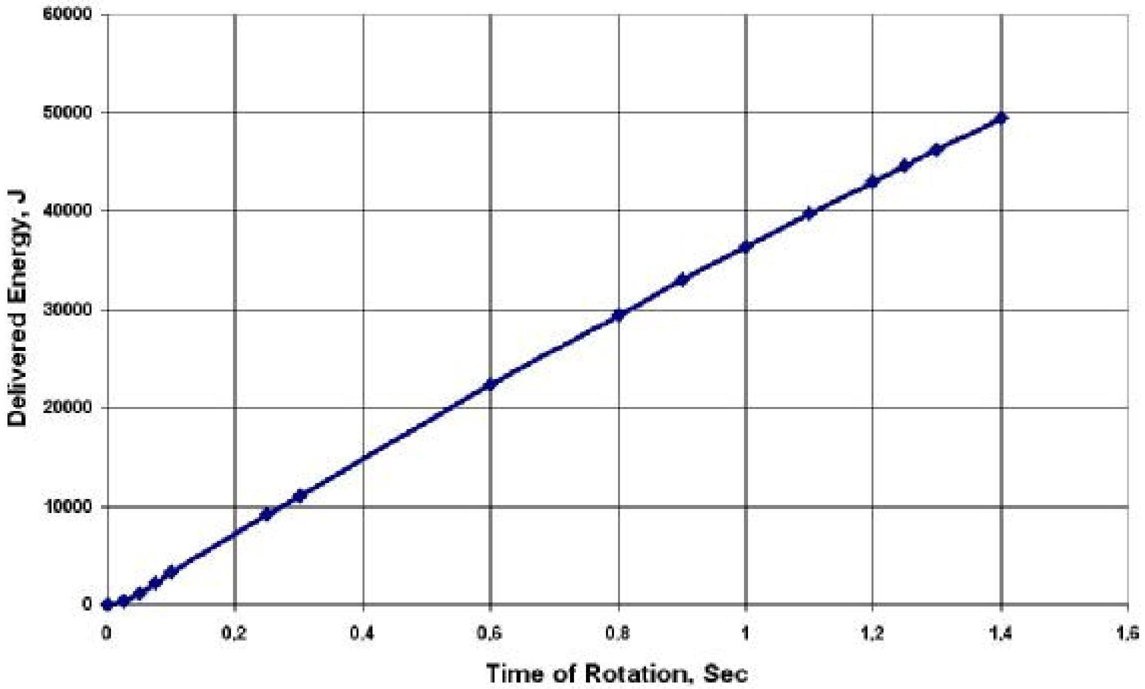

Figure 12. Delivered Energy vs Time. Battery only. SOC ~ 30%.
Engine 1200 h.p. Temp. + 2ºC.

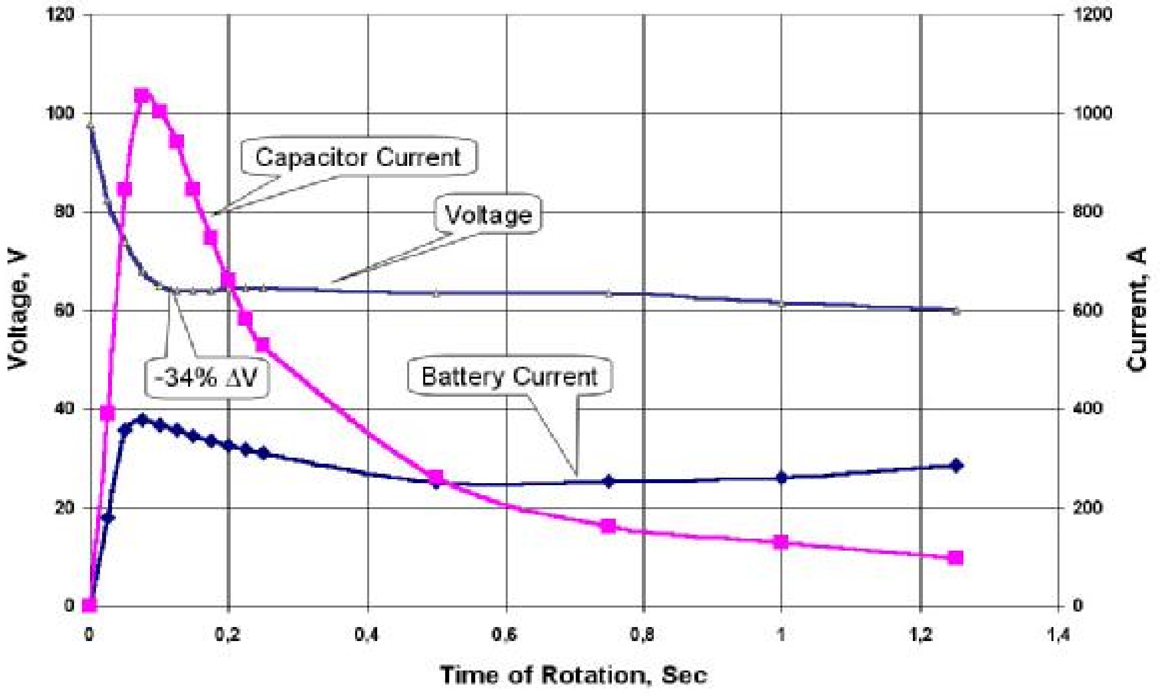

Figure 13. Current/Voltage Profile. Initial Period of Rotation.
Battery + Capacitor. SOC Battery – 30%, Capacitor – 144 kj.
Engine 1200 h.p. Temp. +2ºC.

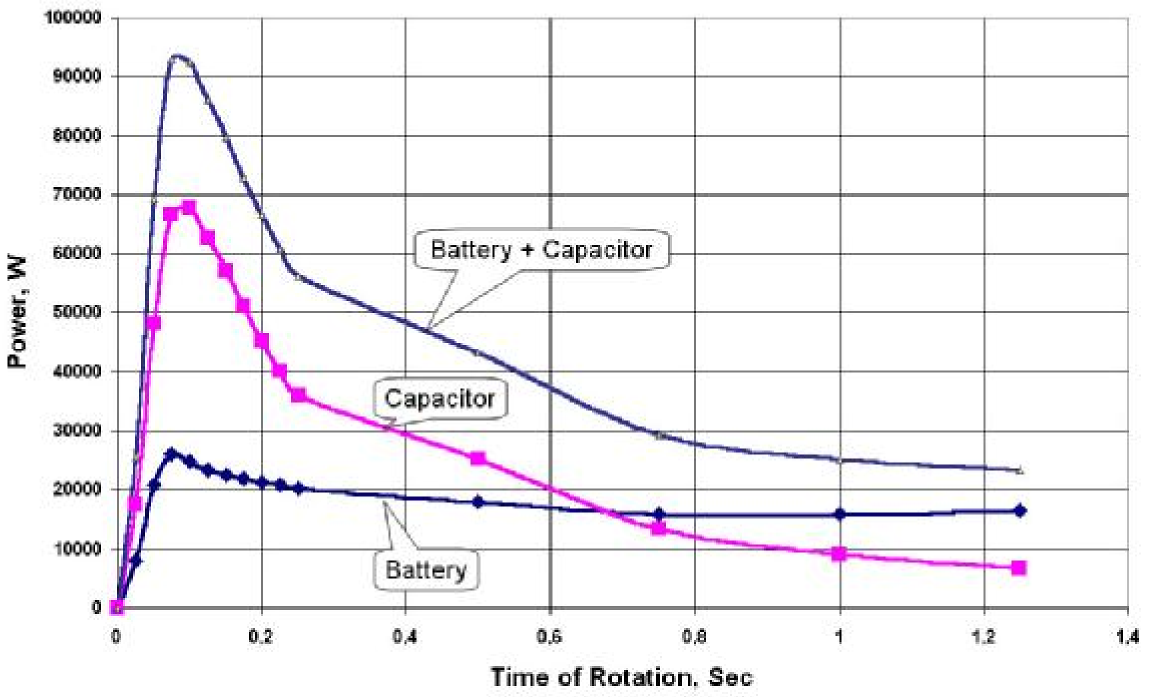

Figure 14. Power Profile. Initial Period of Rotation.
Battery (SOC ~ 30%) + Capacitor 144 kj.
Engine 1200 h.p., Temp. +2ºC.

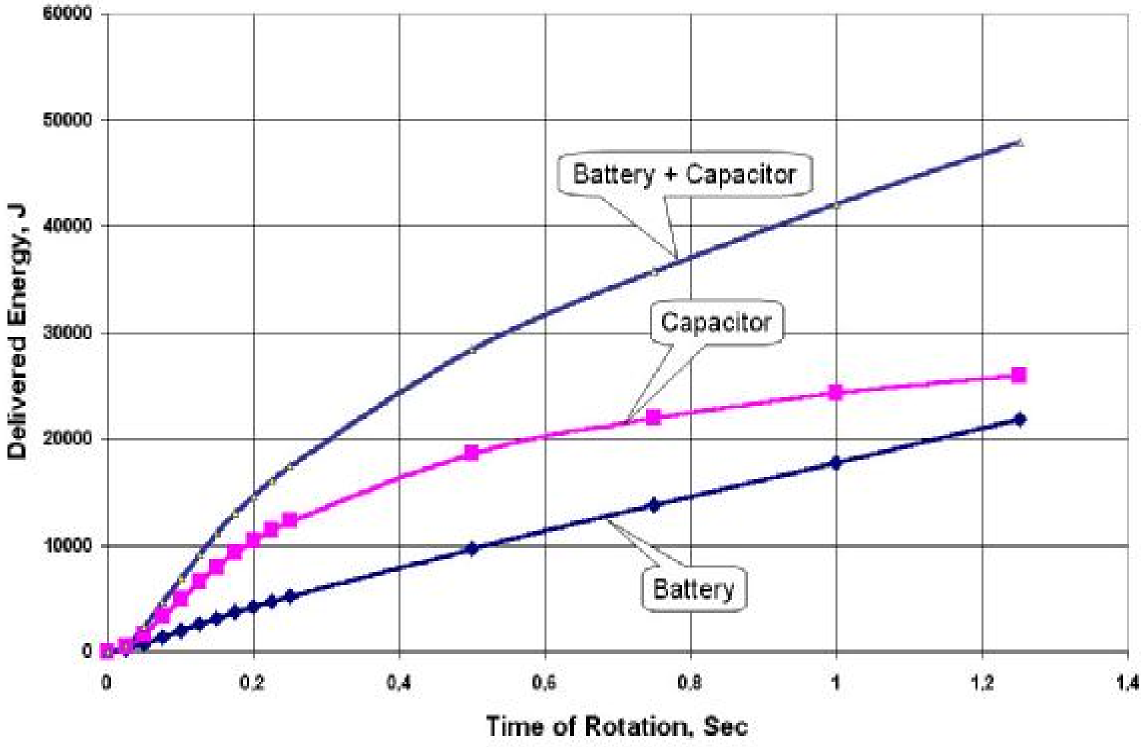

Figure 15. Delivered Energy vs Time. Battery (SOC ~ 30%) + Capacitor 144 kj. Engine 1200 h.p., Temp. +2ºC.