The Sliding Voltage Control Strategy for Power Peaks Bypass

V. Bršlica

Department of Electrical Engineering
University of Defense in Brno
Kounicova 65, CZ 612 00 Brno (Czech Republic)

Phone number: + 420 973 442 319, fax: + 420 973 443 773, e-mail: vit.brslica@unob.cz

Abstract. The variable speed generating units have not enough power reserve for rapid load step-up, when they are operated at low speed with partial load. The short time power peaks delivery during the acceleration period must be provided from separate energy store, which can be among others the ultra-capacitors battery. Standard solution connects the capacitors via DC/DC bidirectional converter. The ultra-capacitors voltage varies in the range 50% what represent 75% exploitation of maximal stored energy. New concept is based on direct connection of ultra-capacitors into the inter-circuit with controlled voltage drift only 30% and 50% energy exploitation. That means the resulting capacitance must be 50% higher, but one converter is saved, efficiency grows up and the control becomes simpler.

Key -Words:

Variable speed generating, ultra-capacitors, converter control, flying voltage, high efficiency

1. Introduction

This paper was prepared as the result of research works in area of variable speed mobile power sources with high resistance to load ripples. It is evident that combustion engine with its typical flat torque vs. speed dependence (Fig.1) has not enough power at low speed to deliver full rated power and under the overload it is not able to accelerate to the high-speed run, where it has sufficient force. The suitable source of power peaks was therefore searched, together with its integration into the original chain of energy conversion. The presented original idea simplifies the system and increases its robustness.

2. Power Peak Sources

After the realistic examination of possible energy stores only two has been found suitable for kilowatts delivery in the few-seconds periods. They are electrochemical accumulator batteries of many kinds and ultra capacitors in the very near future, because of their fast development in the last period.

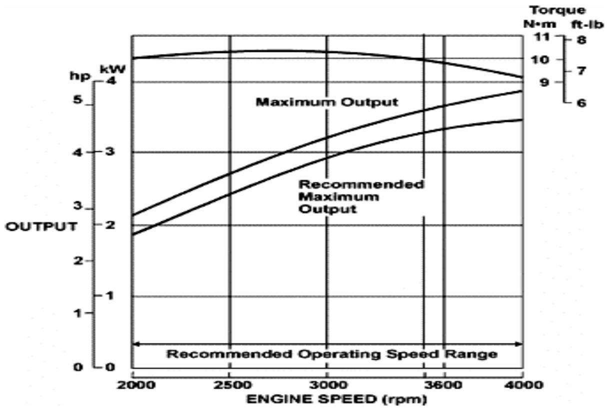

Fig.1 Typical combustion engine characteristics

A. The Indirect Battery Connection

The first realized VSCF model (variable speed – constant frequency) [1] was designed with SGPM (synchronous generator with permanent magnets) and during its testing was found its low stability in load step-up conditions. When power peaks delivery was solved with battery, the cheaper AG (asynchronous generator) was applied [3]. Via the bi-directional AC/DC inverter INV1 in Fig.2 the reactive power from battery can excite AG at any speed. As a power peak source was prepared the set of 24 lead acid sealed batteries 12V, 7Ah in serial with total voltage 300V. Through the DC/DC converter is this power source connected into 600V DC link between two identical inverters (Fig.2.).

The energy stored in this accumulator is very high, its mass is also very high, but real power peak cannot reach over 6 kW, although this peak value can be delivered for long period up to 8 minutes (Fig.3) instead of 2 – 5 seconds, which is the necessary time to engine acceleration, more is in Table I.

TABLE I. – Power peak source parameters

C_5	Batt	I_{max}	Un	P_{max}	T	max	Energy
Ah	V	A	V	kW	min	kJ	kWh
7	24 x 12	21	288	6	6	2160	0,6
		7		2	30	3600	1,0

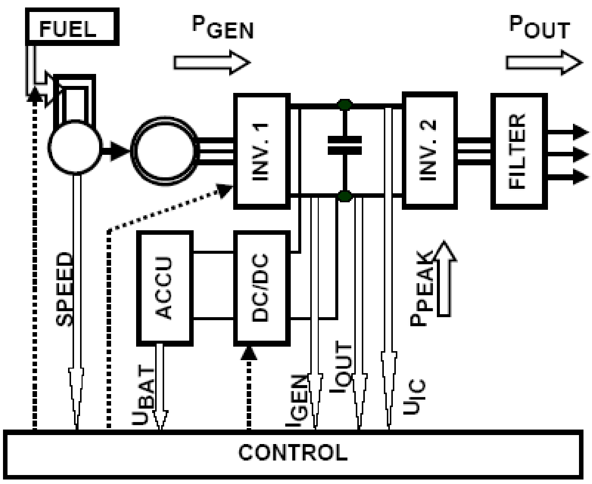

Fig.2 VSCF model with Asynchronous Generator and 300V Battery for Power Peaks Delivery

However the solution with reduced capacity [Ah] and stored energy is not applicable, because the chemical batteries have typically low value of power density [W/kg] (Fig.3).

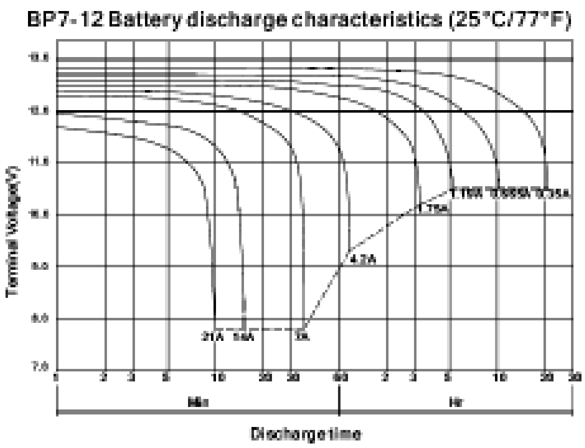

Fig.3 Lead acid 7Ah battery discharge characteristics

Moreover this conception is too complicated for control, when two converters must be controlled in cooperation to keep stabile voltage in DC link.

B. The Direct Battery Connection

The simplification was reached in next configuration of low power model (Fig.4), where is worse efficiency on principle. Therefore the DC/DC converter has been eliminated here and energy from AG flows via INV to DC terminals, where parallel-connected 36V 60Ah battery is stabilizing the voltage. It is also lead acid type, although LiIon batteries application should be better, but much more expensive.

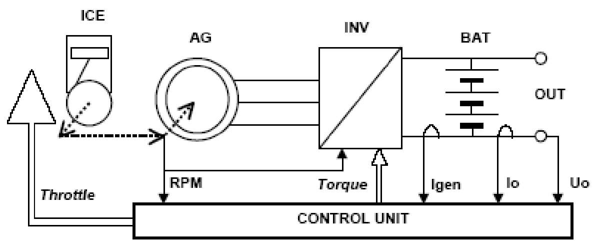

Fig.4 Low Power Low Voltage Variable Speed Battery Source for UPS Supply

The conversion to AC power output is not solved in this model; it is supposed to use standard UPS source, or in the principle any inverter with independent control for keeping constant output voltage and frequency.

C. The DC-link Voltage

In both presented configurations the chemical battery can be replaced by big enough ultra-capacitor with much lower stored energy and short-time discharge consequently. Comparing with the accumulator where the energy is received from chemical energy with constant output voltage in wide range of loads (Fig.3), the capacitor energy is from electrostatic field, therefore any energy take-off from the capacitor results in the output voltage decreasing during the power-peak delivery. The capacitor does not work like voltage stabilizer. The voltage decrease degree can be reduced only in the event, the value of capacitance will be extremely great (if having the infinite capacitance no voltage drift appears).

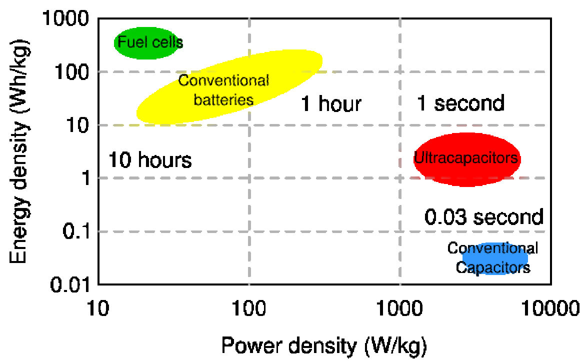

Fig.5 Parameters comparison of electrochemical batteries and ultra-capacitors

The ultra capacitors offer much low energy density (Fig.5), but in supposed application the energy consumption is only few kWs, but high power is demanded and in this parameter they are much better then batteries what means important mass reduction. Also the high cycle efficiency over 95% is great advantage of ultra-capacitor comparing to hardly 60% at electrochemical accumulators.

3. Ultra Capacitor Battery

The actual exploitation of ultra capacitors is still very rare; mostly in experimental transport drives for short distance passenger transport or for urban traffic. It was derived for the optimal efficiency the voltage operational range between top and bottom value in cycle the ratio p = 50% (3), in which 75% of stored energy can be exploited (Fig.6). Further voltage decrease brings no essential energy profit, because the DC/DC converter efficiency falls down growing voltage ratio.

Three input values must be known for correct capacitor design:

- maximal voltage U_{MAX}
- maximal power P_{MAX}
- and maximal discharge period Δt_{MAX}

The total energy in the capacitor is described:

$$W_{MAX} = \frac{1}{2} C U_{MAX}^2 \tag{1}$$

The gain-able energy during discharging, without any losses, when voltage falls from U_{MAX} to U_{MIN} can be described like that:

$$\Delta W = \frac{1}{2} C (U_{MAX}^2 - U_{MIN}^2) = \frac{1}{2} C U_{MAX}^2 (1 - p^2) \tag{2}$$

where

$$p = U_{MIN} / U_{MAX} \tag{3}$$

The voltage decrease is not linear at constant output power and this time function can be seen in Fig.6.

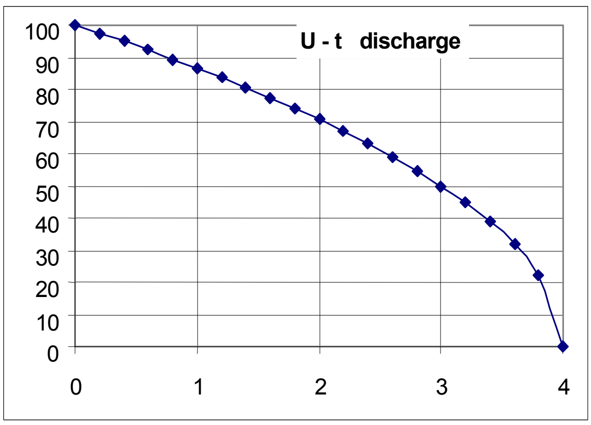

Fig.6. Capacitor voltage at constant power discharge

Similarly for the p = 70% (Fig.6) the energy gain is ΔW = 51% and such voltage fluctuation is common in the inter-circuits of frequency converters for AC controlled drives. The voltage fluctuation reduction from p = 50% to p=70% results in the need of greater capacitor to achieve equivalent energy. The capacitance increase should be 50% as can be also understand from the Fig.6.

The energy decrease depends on the power P:

$$\Delta W = P\, t = \tag{4}$$

The voltage can be from (1) calculated:

$$U = \sqrt{\frac{2W}{C}} = \sqrt{\frac{W_{MAX} - P.t}{C}} \tag{5}$$

If the great capacitance of ultra-capacitor appears in inter-circuit, the voltage drift becomes much slower and easy to control. Instead of control on the middle value of allowed interval, the control can be adapted for the purpose exploitation of all the voltage range according to output power – instantaneous load.

The voltage interval is graphically presented in Fig.7 where for rated value of AC voltage 400V/ 50Hz is minimal value in DC link U_{MIN} = 560V and for p=70% is the maximal operating value U_{MAX} = 800V. The breakdown voltage 880V should be thoroughly watched and any way prevented its achievement. Therefore is parallel to ultra-capacitor connected the Sv (security switch) with resistor R (Fig.8) activated at any attack to the voltage level $U > U_{MAX}$.

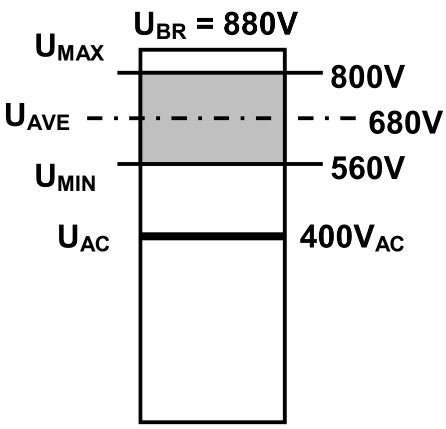

Fig.7. Capacitor allowed voltage for constant AC output 3x400V with breakdown DC limit 880V

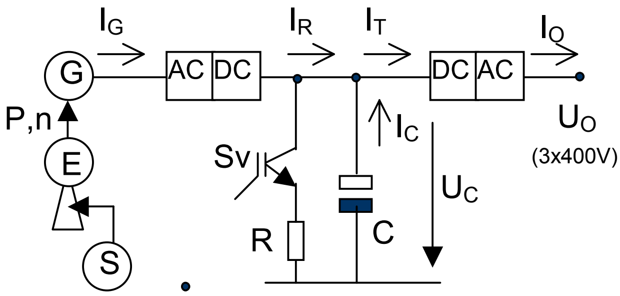

Fig.8 Energy flow chart around the capacitor with sliding voltage at variable power output

The proposed ultra-capacitor connection (Fig.8) into the structure from Fig.2 remains more then original structure, the low voltage concept from Fig.4. Only the inverter control should be optimized to eliminate all voltage divergences because the capacity in standard converters is not very high and every break of defined limits can cause the breakdown with next damages.

Another problem can be the high voltage, because the ultra-capacitor battery consists of many cell with only 2,5V per cell. To keep uniform distribution of voltage can cause next problems, but from last information they are realized some vehicle applications with 640V battery (operating range is from 670 to 360V) and manufacturer limit in-string operating voltage is now 1500V DC.

Looking in Table I. and assuming the acceleration period under t_a = 5s the maximal power peak energy is:

$$\Delta W = P\ t = 6000\ .\ 5 = 30\ 000 Ws \qquad (6)$$

Calculating 50% energy gain the maximal necessary energy is:

$$W = 2\ \Delta W = 60\ 000 Ws \qquad (7)$$

The minimal capacitance should be for one 125V ultra-cap pack only 8F (Fig.9) and such blocks in our model must be at least 6 for 750V only.

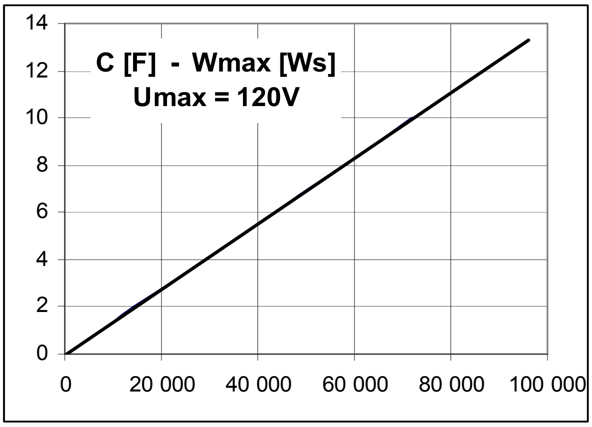

Fig.9 Capacity vs. total charge power

Much greater blocks are to disposal as can be seen in Table II. If this 63F block has the mass about 50 kg, the sufficient 8F block can be about 6kg and next capacitance increase is still acceptable, moreover it brings the voltage range decrease. Optimal capacitance must be compromise.

Table II. HTM series 125V parameters

Nominal operating voltage	V dc	125
Maximal operating voltage	V dc	135
Surge voltage	V dc	142
Nominal capacitance	F	63
DC resistance	mΩ	14,0
Energy available	Wh	101,7
Self discharge (70% of initial)	days	30
Max continuous current	A	150
Max current (75% discharge in 5 s)	A	750
Life time (125V)	h	150 000
Cycles (125 – 62,5V)		1 000 000

4. Sliding Voltage Control

The control strategy fundament is very simple. If the load is near the minimal value, only the load increase can be expected, therefore the capacitor should be maximally charged and its voltage value has to be kept on maximal value. Oppositely, at loads near the maximum, only the sudden unload can be expected, which can cause the Diesel engine over-speeding and minimal charge of capacitor can help to catch the surplus power.

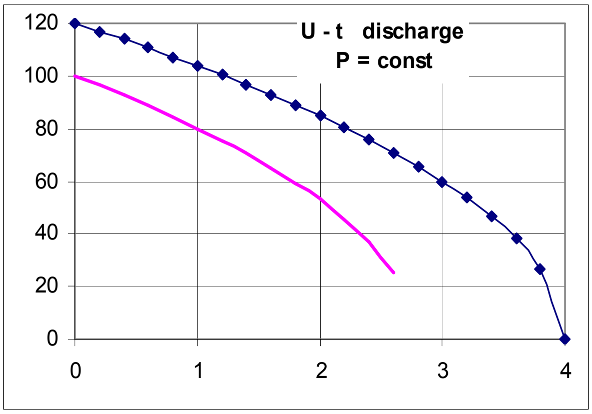

Fig.10 Capacitor voltage at constant power discharge (1800W, 1F, 100 – 120V)

The second reason for keeping maximal voltage is shown in Fig.10. It is clear, that twenty percent higher starting voltage value can bring more then twice more energy comparing with lower voltage value. And what is very important is the voltage at the end of power peak delivery period, because it must over the U_{MIN} value, otherwise the output voltage U_o magnitude is endangered. The reason is in sin wave modulation as is illustrated in Fig.11.

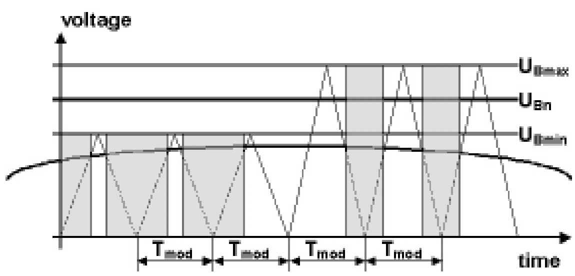

Fig.11. PWM voltage modulation at varying ultra-capacitor voltages

Illustration of power flow control can be easily seen in Fig.12, where in the time T_1 appears the load step up. Promptly is closed INV1 and unloaded generator starts its acceleration during the t_{a+} period. In the time instant T2 the speed of generator (and engine) is corresponding to new load and generator is charged again, but its output is controlled not to increase the ultra-capacitor voltage.

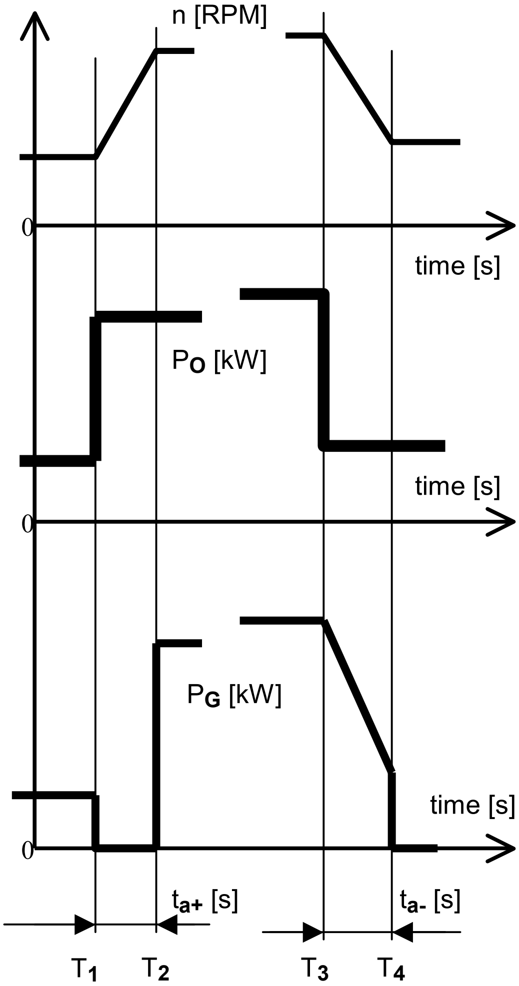

Fig.12 Transients of speed and power flow after load jumps

After some period in the time T3 appears load step-down. Generator is not switched off, but the engine torque is reduced and speed falls down to new corresponding speed. The power surplus serves to recharge of ultra-capacitor on high voltage again.

5. Conclusion

The suggested direct wiring of ultra-capacitors into DC link represents maximally simplified hardware with principally higher efficiency. The controller also results simpler.

The necessary effort should be directed to coordination of rated values for prepared new, not typical ranges of ultra-capacitors batteries production.

The minimal volume and price of ultra-capacitors for proposed system is only 50% greater then for classical system with charge pumping by additional DC/DC converter.

Conventional battery advantage was great engine starting ability. To keep this advantage maybe the ultra-capacitors capacitance will be artificially increased not from the power peaks point of view but also from very comfortable and reliable engine starting via generator in motor mode. The capacitance increase brings lower voltage swing and upper value U_{MAX} reduction with positive consequences.

Pre-charge of great capacitor must be also solved; it needs a lot of energy and expected way of optimal energy management cannot rely on the low self-discharge, although it reaches now more then 30 days on the level 70%.

Acknowledgement

Financial Support of University of Defense in Brno, Research Program No VZ-0000403 is acknowledged

References

[1] Bršlica,V., Variable Speed Asynchronous Generator, in Proceedings of ICREPQ 2004, Barcelona, Spain 31.3. – 2.4.2004, 8 pp., ISBN: 84-607-9887-9

[2] Bršlica,V., Power peak sources for isolated network In Proceedings of ICREPQ 2005, Zaragoza, Spain, 7 pp., ISBN: 84-609-3234-6

[3] Bršlica,V., Battery Charging from Variable Speed Asynchronous Generator In WSEAS Transactions on Systems, Issue 8, Vol. 4, Corfu, Greece, August 2005 pp 1363-1367, ISSN 1109-2777

[4] COST Action 542

[5] Maxwell

[6] SEGELEC

[7] Siemens, EPCOS

333-brslica