Power peak sources for isolated network

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Abstract. In the little area networks with one generator, any greater power step in load causes energy quality problem, namely if in GEN-SET (Generating sets) the modern VSCF technology (variable speed - constant frequency) is used to reach the fuel consumption saving. The voltage stability is improved there, thanks the frequency converter output, but another problem appears - engine cannot accelerate from low speed at higher power step-up load. Possible solution of peak-power delivery into VSCF system (from accumulator, inter-circuit capacitors or ultra-capacitors) is main task of this paper.

Key words

VSCF Gen-sets, DC/DC converter, accumulator battery, power-peaks injection, ultra-capacitor

1. Introduction

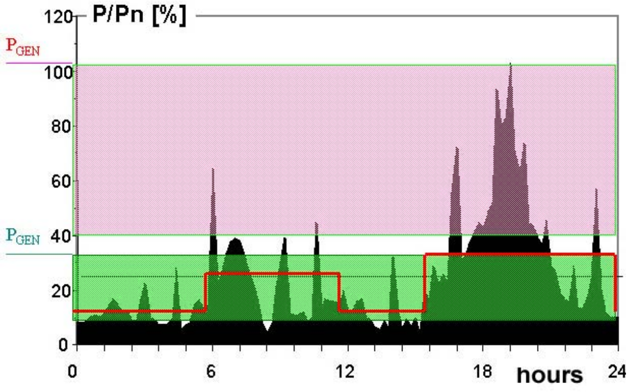

Fig.1 Typical daily load diagram of Gen-Set in one source local net

Little area electrical network, out of the grid, use to be supplied from rotating sources driven by combustion engine. Gen-Sets with synchronous generator (SG) directly connected to load are most known. Voltage is field current controlled, frequency is given by engine speed control. Load-steps cause speed faults, which are reflected in frequency and voltage faults consequently. To keep fault values in allowed limits means over-dimensioning of all the system, moreover for constant frequency must engine run all the time with constant (full) speed, although the average load is about 25% of rated value. The low load run is therefore substantive during longer part of all the day (Fig.1) and all this time it works out of optimal fuel consumption [g/kWh]. Thanks high speed it makes much more revolves than at reduced speed, therefore it is sooner tired-out.

From 90-ties the research works have been started on the VSCF technology, which brings power converters integration into rotating sources to change (variable) generated voltage and frequency into constant output [1,2]. The added losses in converters are in total efficiency account compensated by zero losses in SG field coils and zero exciter losses (they do not exist more) when SG with permanent magnets (SGPM) is used.

The VSCF sources offer economical advantage in fuel cost reduction and higher output power quality (parameters stability), ecological advantage is in emission reduction (noise, exhaust) [3]. Disadvantageous appears low overload stability first of all, the low value of allowed power-peaks. To improve this situation the research project has been granted.

2. Variable speed GEN-SETS

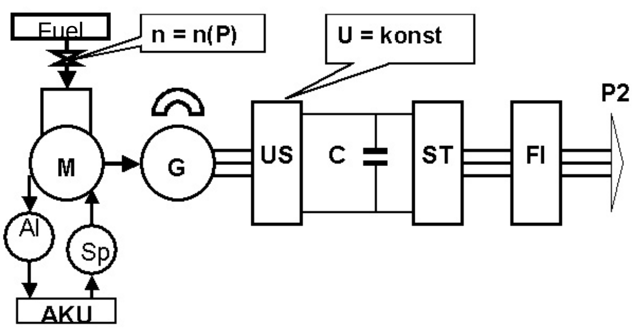

Fig.2 VSCF source basic configuration, (abbreviations: Al = alternator, Sp = starter)

Variable speed sources are common in other applications many years, known are car generators and Diesel-electric traction, but there are some important differences here. The car generator delivers constant maximal power in all the speed range with always enough driving power from engine. In traction the speed can be sooner increased, then the load power grows up oppositely to sudden switch-on load in GEN-SETS (first load switch, then speed increase).

Basic configuration of VSCF source in Fig.2 shows following blocs: rectifier US, capacitor C in the inter-circuit, and converter ST. Because the converter output voltage is not enough harmonic (smooth) there is the filter FI (or transformer) at the end. Generator needs no control, because variable speed anyway gives non-constant, speed dependent, voltage:

$$U = 4{,}44 \frac{p.n}{60} \Phi N k_v \qquad (1)$$

and permanent magnet PM field can be used with advantage. To keep low volume of expensive PM the multi-pole configuration must be used [4] which results in higher frequency (up to 400 Hz).

Rectifier and converter reach very high efficiency; still they represent in the energy conversion chain additional elements and the losses saved at SG excitation are dissipated in here. All the energy saving must be then reached in engine by optimal speed operation.

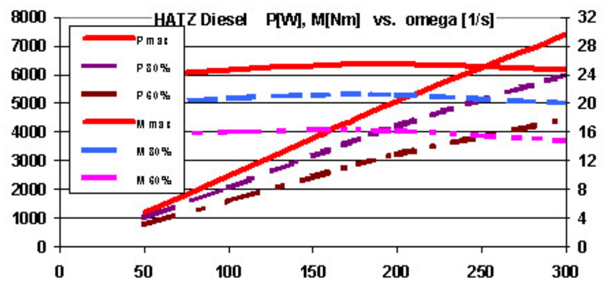

Fig.3 Diesel engine HATZ 1D50 Torque [Nm] and Power [W] vs. ω, for dosing 22 - 18 - 14mg (model results)

A. Driving engine

With the exception of very low power (under 2 kW) all new Gen-sets are actually Diesel driven, thanks its higher efficiency, because the fuel cost represents substantial part of generated energy price. Typical Diesel engine characteristics are in Fig.3, (namely for HATZ 1D50 which is build in our model). Presented maximal values are for full dosing injection (22 mg) and dosing reduction leads to torque and power decrease consequently Fig.3. Torque reduction brings power reduction and because, at given speed, the unchanged thermal and mechanical losses must be subtracted, the efficiency decreases rapidly. It can be better followed in Fig.4, where is for constant speed the fuel consumption increase at decreasing load clearly visible, or another way said for every output power the optimal speed can be estimated. Because the minimum is very flat, see Fig.4.b any run with jet dosing over 40 - 50% of maximal value can be accepted [5]. That explains the economical areas in Fig.1, where the upper area is for full speed (power from 100% to 40%) and the lower one for 33% reduced speed.

There is evident from Fig.3 that the maximal power output of Diesel engine at low speed is much lower than the rated one, therefore at sudden power step–up the GEN-SET cannot deliver its rated power, not even with such overload accelerate to the higher speed, which gives demanded power. To allow engine's acceleration it must be temporarily discharged and uninterrupted power delivery in this period must be assured from additional auxiliary source - PPS (Peak Power Source). Simplest PPS plug-in block is in Fig.5, created by accumulator AKU2 and DC/DC converter.

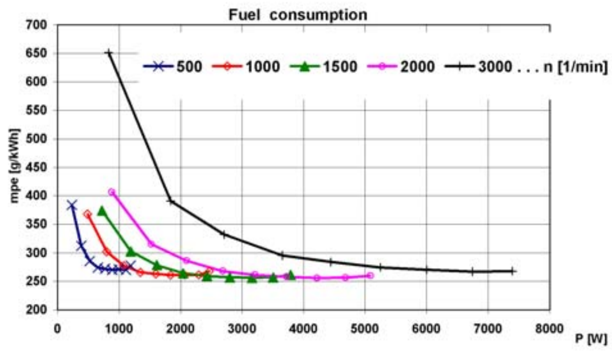

Fig.4a Diesel engine HATZ 1D50 Fuel consumption at various speed. Each characteristic has the same jet dosing values charted: 6 – 8 – 10 – 12 – 14 – 16 – 18 – 20 – 22 g (from left to right)

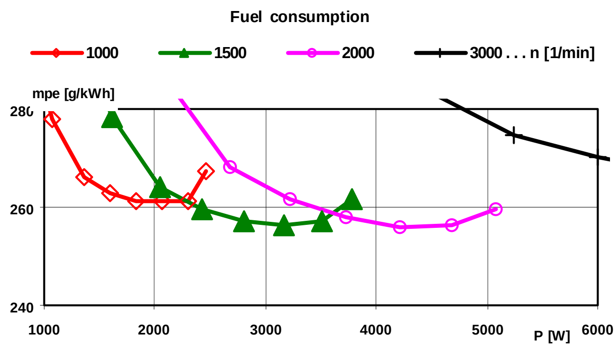

Fig.4b Fuel consumption dependence detail in optimal region from Fig.4a

3. Peak Power Source

Classical Gen-Set frequency stability is given by generator speed stability. To reduce speed drift the higher inertia is suitable, because the free-wheel energy delivers power peak in transient period of torque increase (received by jet dosing enlarge in Diesel). Speed stability in VSCF sources is not necessary; therefore the inertia has not been artificially enlarged over the value given by engine property. Freewheel for peak power delivery is possible to use, but out of main machines, because it can give energy only from deceleration, and VSCF generator must accelerate to higher speed for higher power.

Rotating accumulators are not yet in market offer and in the next only electrochemical ones will be supposed, which are also used for Diesel starting in actual Gen-Set. Their use in here only should be more frequent and maybe greater capacity is necessary. Last ten years there is a big progress recorded in the area of electrochemical accumulators, namely for communication means and for UPS sources (Uninterruptible Power Supply).

UPS sources are in principle of the same structure as is in VSCF sources applied behind the inter-circuit and UPS can be here used with advantage, as is described later. In Fig.5 is UPS represented by blocs: AKU2, DC/DC, C, ST and FI.

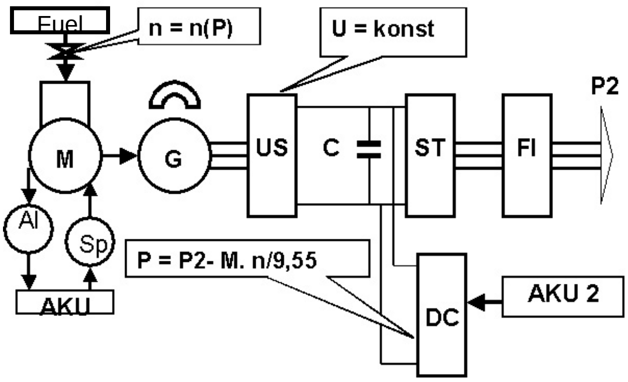

Fig.5 PPS (AKU2+DC) connecting into VSCF source system

A. Pulse Rectifier

Diode rectifier is not sufficient for variable speed generator to keep constant voltage in inter-circuit. Controlled rectifier is not optimal too because it can only decrease the input voltage value, therefore generator must be designed for high voltage with isolation problems. Our first solutions (Fig.2 and Fig.5) are based on diode rectifier followed by DC/DC step-up converter to keep constant voltage on capacitor C.

Moreover the standard rectifier loads generator by non-harmonic current, which causes Joule losses increase and efficiency decrease consequently.

Pulse Rectifier [6] is able to load generator by harmonic current. In principle it is voltage inverter (Fig.6) operating in fourth quadrant and transporting energy from lower voltage generator to DC inter-circuit with higher voltage in one conversion step:

$$U_{DC} > 1{,}4 * Us_{GEN} \qquad (2)$$

This condition is very important namely for SGPM, where is no voltage reduction by field weakening possible and if voltage is over, the back diodes create standard uncontrolled rectifier with all its negatives.

Accumulator in DC inter-circuit stabilizes voltage between charge and discharge values, but if there is only capacitor there, its voltage drifts in dependence of current balance. When the generated power is over the loading power, the voltage grows up and vice versa. The load is stochastic and the voltage stability is kept by feedback control of pulse rectifier.

Synchronous generator has always full-flux induced voltage, but asynchronous generator AG must first be excited by magnetizing current from pre-charged capacitor, so the pulse-rectifier first supply reactive power to AG (inverter) and then active power can deliver back to load capacitor. If there is some PPS to disposal to pre-charge C, the cheaper and more robust AG is preferable also for its better cooperation with inverter rectifier because no synchronism is necessary and reduced flux can be used at reduced power [7].

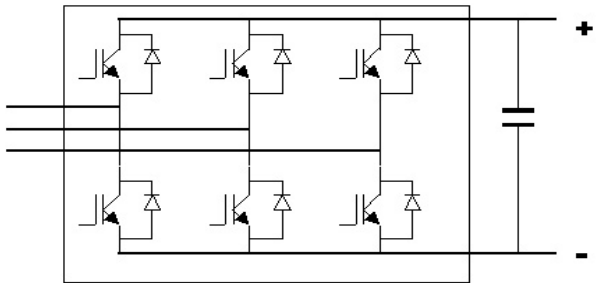

Fig.6 Pulse Rectifier (Ugen< Udc) replaces Diode Bridge and DC/DC Step-up Converter.

4. Power source dynamics

Dynamics solution is based on torque equilibrium and because the load steps are stochastic, the system must be able to supply rated load at any instant without interruption or decrease of power. Most of daytime GEN-SET is operated at load under 20%Pn (Fig.1), it is at minimal speed, which is about 25-30% n_n for common stabile Diesel engine.

A. Peak Power and Energy

Peak power limit is reached, when GEN-SET is full loaded in one step from no-load. Instantaneous step-up in output power causes diesel torque increase in short time, dependent on the mechanical speed of throttle. Maximal torque still gives at minimal speed ($1/3n_n$) only one third of rated power (Fig.3) because:

$$P_{mot} = M_{max}\left(\frac{n_n}{3}\cdot\frac{1}{9{,}55}\right) \qquad (3)$$

Such unbalance brings the stop the entire generating unit, until the other source is not used to deliver power difference enabling engine acceleration to higher speed, which is sufficient to get power adequate for actual load.

Some rare loads (as is the starting up of asynchronous machine) can reach for a short time the values over rated power. PPS must be able saturate this values too; in classical Gen-Set the bigger engine power is used, which assures 130-150%Pn, generator has no problem with short time overload.

B. Peak Power Source Dimensioning

Fastest acceleration can be reached at zero-load; it means engine unloading and delivery all the Gen-Set output energy from PPS, during the acceleration. It results the rated power of PPS equal to Gen-Set rated power (or more). For the PPS energy estimation, the acceleration time must be calculated from formula:

$$M_a = J\ (d\omega/dt) \qquad (4)$$

From where for time results:

$$dt = (J/Ma)\ d\omega \qquad (5)$$

Acceleration torque (at zero generator power) equals maximal engine torque. Speed step-up for worst cause is from no-load (1000 rpm) to rated speed (3000 rpm), which results:

$$\Delta t = (0{,}2/20).\ (300\text{-}100) = 2\ s \qquad (6)$$

Energy is given by power and time as follows:

$$W = P_{max}.\ \Delta t = 6000\ .\ 2 = 12\ kJ \qquad (7)$$

Such energy is not very much for common accumulator, but there is necessary to take into account the internal resistance and voltage drop. This is the limitation of peak power, well known from lead acid starting battery, where is labeled as starting current [A] and its value is about five times of capacitance [Ah] for 10s peak load. In the UPS sources only three times capacitance is used as is clear from Table I.

TABLE.I. Lead Acid Accumulator Batteries for PPS

C5	Imax		Un	Pmax	t	Wmax
7 Ah	20 A	4x 12 V	48 V	1 kW	10 min	600 kJ
7 Ah	20 A	8x 12 V	96 V	2 kW	10 min	1200 kJ
7 Ah	20 A	24x 12V	288 V	6 kW	10 min	3600 kJ
40 Ah	120 A	4 x 12 V	48 V	6 kW	10 min	3600 kJ
40 Ah	20 A	4 x 12 V	48 V	1 kW	120 min	7200 kJ

UPS standard batteries are compared here with starting car battery 40 Ah. It is evident, that total capacity is more than sufficient and for small loads under 1kW Gen-Set can be operated for long hours without running engine.

C. Accumulator or Ultra-Capacitor

The main advantage of accumulator (with high enough capacity) is the repeated stop and start of engine for long periods when Gen-Set load is minimal and can be completely provided in UPS run. Battery can be completed for any voltage, but in praxis is the voltage 560V used for big power only (over tens kW). From price point of view there are lead acid batteries with 5 or 10 years lifetime most economical.

Ultra capacitors are relatively new, therefore expensive, but with practically unlimited lifetime, much higher efficiency of charge/discharge cycle and much higher peak power value. Such properties are used with advantage in peak power accumulation and back delivery in traction drives, with variable voltage principally, but it is no problem for electronics. On contrary to classical C (electrolytic) their energy density is ranges higher; disadvantage is very low voltage for one cell and only 100V batteries are produced and their serial connection is not recommended without extra checking. Ultra-capacitors use in Gen-Sets seems to be very perspective, namely in good cooperation with accumulators, because starting power (only 2kW) can be supplied from common small accumulator and the rest 4000W added for 2 seconds (it is 8000J for one peak) from capacitor.

Energy from capacitor can be described:

$$W = \tfrac{1}{2}\ C\ (U_1^2 - U_2^2) \qquad (8)$$

Supposing $U_2 = \tfrac{1}{2} U_1$ for 100V battery the minimal capacitance is:

$$C = (2\ .\ 8000)/(100^2 - 50^2) = 2{,}2\ F \qquad (9)$$

100V battery consists from 40 cells a 200F (Table II.) in series and its capacitance is:

$$C = 200\ /\ 40 = 5\ F \qquad (10)$$

The reserve is sufficient and the total mass of such ultra-capacitor is only 2,2kg.

TABLE.II Ultra-capacitors from EPCOS trade

C	Umax	Imax	m	Wmax
5000 F	2,5 V	500 A	850 g	15625 J
2700 F	2,5 V	500 A	600 g	8438 J
1200 F	2,5 V	300 A	300 g	3750 J
600 F	2,5 V	300 A	160 g	1875 J
200 F	**2,5 V**	**50 A**	**55 g**	**625 J**
10 F	2,3 V	3 A	6,4g	26,5 J
5 F	2,3 V	2 A	5,5g	13,2 J

5. No Accumulator PPS

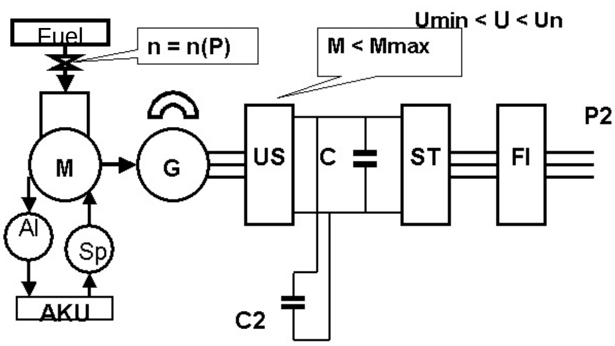

Fig.7 Peak power energy from inter-circuit capacitor, US must reduce generator load

The same principle of peak power delivery as is presented for ultra-capacitor, can be used if inter-circuit voltage variation is permitted (Fig.7). Lower limit U_{min} is given by converter output voltage. The upper one U_n is breakdown voltage of capacitors and semiconductors. For output voltage 3 x 400V the lower limit value is:

$$Umin = 560\ V \qquad (11)$$

And the upper one can be posted:

$$Un = 750\ V \qquad (12)$$

To have some reserve for safety-switch watched over-voltage, which is 770V.

The same way as in (9) for peak energy 12 kJ (7) the necessary capacitance results:

$$C = (2\ .\ 12000)/(770^2 - 560^2) = 0{,}1\ F \qquad (13)$$

Which is in electrolytic capacitors set (100 mF, 800V) very big volume and weight for small 6 kW Gen-Set, but in ultra-capacitors it is only small pack.

The rectifier must be again able to close (or limit) the energy delivery from generator for rapid mechanical acceleration.

6. Intelligent GEN-SET

PPS integration as is in Fig.5 offers more new profit than is the stability. Intelligent control can be applied with advantage, for autonomous Diesel start and stop in dependence on power output and battery charge. Generator can be used in motor mode for starting, as is usual in Diesel electric traction drive.

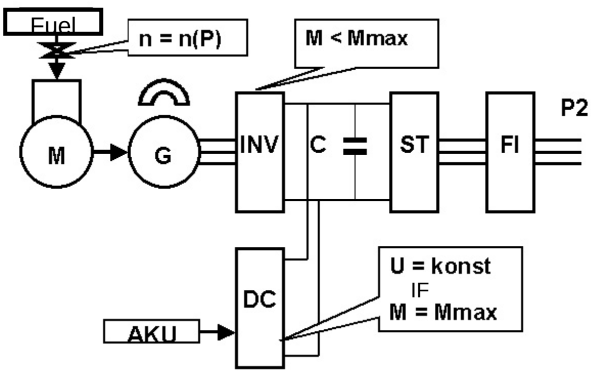

Fig.8 Gen-Set model with rectifier – inverter that can also start the engine

Pulse rectifier from Fig.6 that is implemented to get harmonic generator current can serve as converter and no auxiliary electrical machines on Diesel are necessary more. The Gen-Set became simpler and cheaper (Fig.8 vs. Fig.5) without starter and low voltage generator.

Having accumulator to disposal, SGPM is not unique solution; much cheaper and more robust asynchronous machine can be used, with simpler inverter control.

A. Asynchronous Generator AG

Asynchronous generator with capacitor excitation is used in Gen-Sets more than 20 years, but principally in such configuration is not suitable for speed reduction, because the lower frequency, the higher capacity must be connected to reach the same magnetizing current.

Only the four-quadrant inverter gives chance to AG and other passive generators without self-flux source (e.g. switched reluctance, hysteresis, etc.) come back to Gen-Sets.

With advantage can be used 4-pole bulk AM, Δ connected 3x 230V at speed n = 1500 rpm which at double speed 3000 rpm get 100 Hz and Δ 3x 400V at slightly reduced flux density. Only its rotor must be better mechanically balanced. Principal wiring is in Fig.9 and two identical units INV, ST (standard AC drives inverters) are the next advantage.

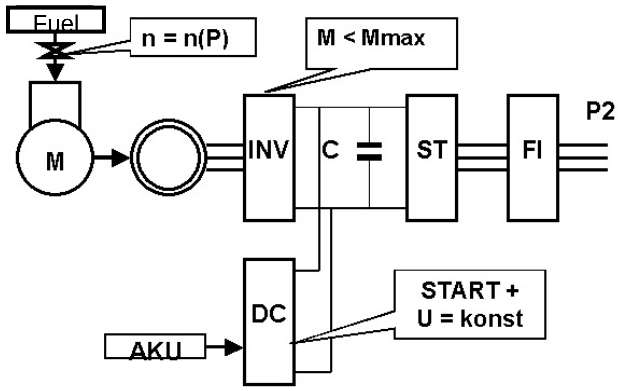

Fig.9 Gen-Set model with AG and pulse-rectifier (inverter), also used for engine start

B. START-STOP system economy

The biggest advantage of high capacity accumulator is the possibility to let asleep engine for hours during the low load period and all the power let deliver only from battery. In the case when either power output is too big or the battery capacity falls under given value the engine is started up. The starting is realized via inverter INV and generator G in motor run. The simulation results of such INGES (Intelligent GEN-SET) supplying load from Fig.1 is in Fig.10. Two different batteries are supposed here, one 300V, 7Ah, and other 600V, 7Ah.

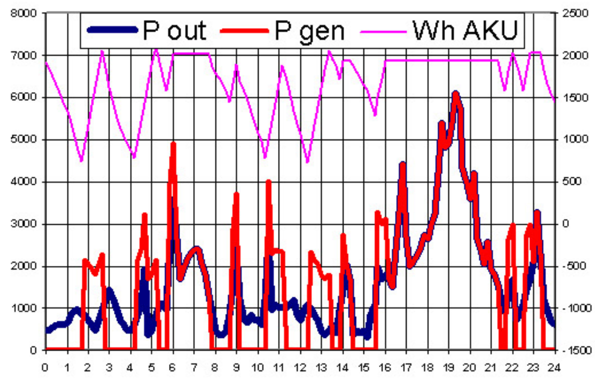

Fig.10a INGES from Fig.8 with 2000Wh battery supplying load from Fig.1

The bigger battery the smaller number of starts in one day and shorter total run of engine. In Fig.10a can be seen 3 generator statuses. Still stand generator, generator supplying load and battery and generator supplying only output terminals. There are too reasons for the third situation, either the battery is full and load is too high, or the battery is not full yet, but load is too high and engine has no power reserve.

The version of 4000Wh battery is presented in Fig.10b where two levels of battery charge currents can be seen.

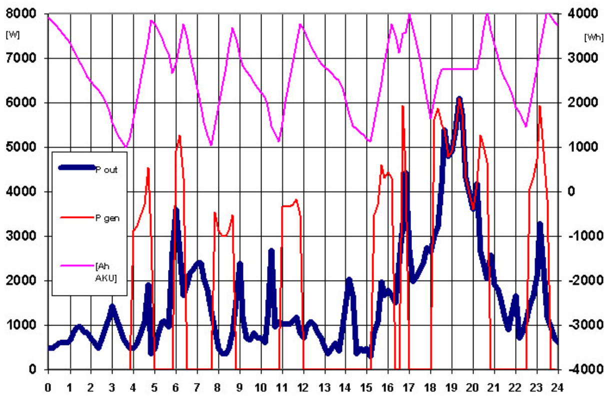

Fig.10b INGES from Fig.8 with 4000Wh battery supplying load from Fig.1

Battery discharge is load dependent; battery charge is supposed linear with constant current or, in the case of 4000Wh battery with current reduction at high load, as can be better compared in Fig.10c. The fast charging is not very suitable for lead acid accumulator oppositely to NiMH and must be verified in long time laboratory tests regarding to the battery lifetime.

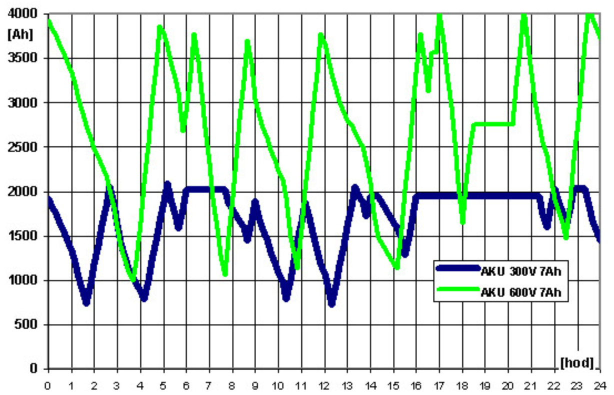

Fig.10c Batteries charge and discharge in INGES from Fig.8 supplying load from Fig.1

However comparing this two versions it is evident, that bigger battery capacity brings starts number reduction as well as total run time decrease Tab. III.

TABLE. III 24 hours INGES loading in accordance with Fig.1

Battery capacity	Number of Starts	Total run time
[Wh]	[-]	[h]
2000	10	13.6
4000	8	8.6

C. Extra Low Voltage Generator

As is mention above, there is not optimal for smaller power Gen-Sets to use 560V battery, but DC/DC converter remove can be reached by use of extra low voltage generator (re-wound stator AM) similar as in electric scooter [9], which was inspiration to this solution.

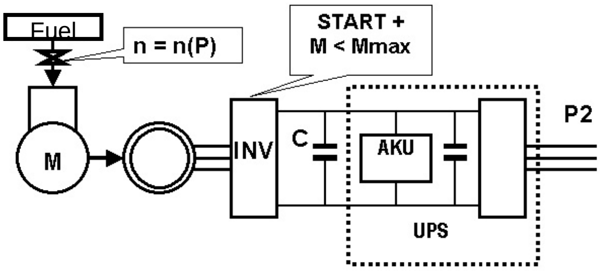

Fig.11 GEN-SET model with extra low voltage AG and inverter directly connected to battery 48 V, power output via external UPS

This model is realized with petrol engine drive for output power 2 kW, and battery voltage 48V given by external UPS Fig.11. Inverter is built with MOS FET transistors.

7. Conclusions

Peak power delivery for step-up load increase can be solved many ways with different price and consequent advanced functions.

Accumulators suitable for peak power delivery improve also starting capacity of Diesel and moreover their energy can be used in UPS battery run regime, which together with START-STOP system minimize the fuel consumption, eliminates no-load run and leads to Intelligent Gen-Set (INGES). Desired INGES characteristic is in Fig.12.

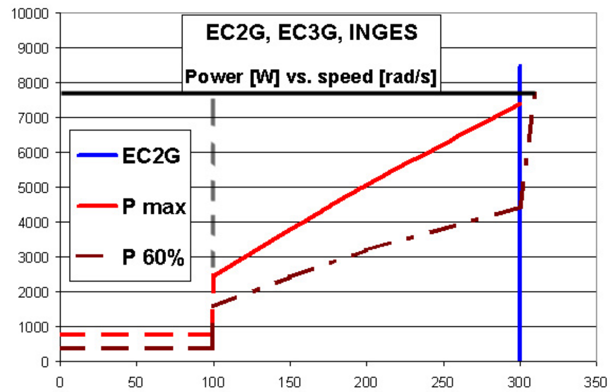

Fig.12 The comparison of 3 GEN-SET generations with rated power 6 kW. EC2G (constant speed) EC3G (VSCF) and INGES (VSCF+PPS) respectively

New technology of ultra-capacitors allows realizing the configuration with variable voltage in inter-circuit or short time, low energy PPS.

Verified variable speed AG function without fix-connected battery to the inverter makes able to leave expensive SGPM.

All presented solutions are based on the realized Gen-Set model in our laboratory, which is step by step modified and tested.

PPS application in Gen-Set causes more complicated control of all the system.

Acknowledgement

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