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Hybrid UPS Based on Supercapacitor Energy Storage and Adjustable Speed Generator

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Summary: **Paper presents hybrid on-line UPS system (H-UPS). Presented system is based on a on-line (double conversion) UPS. H-UPS consists of two controlled energy storage systems. The first one is a static energy storage system based on supercapacitor bank. The second energy source is adjustable speed generating system supplying DC link voltage. A control concept of the UPS operation, according short and long failure of the supply utility voltage is developed. The 5 kW H-UPS is designed, built and tested. The control unit is built using DSP processor based on Shark from Analog Devices. The design and system stability tuning is achieved using PSIM software. Laboratory tests confirm high quality of the produced AC voltage during transients (voltage failure) and during steady state operation without external supply voltage.**

Keywords:
Genset,
Hybrid UPS,
Supercapacitor Energy Storage,
UPS,
Variable Speed Generating System,
VSIG

I. INTRODUCTION

The uninterruptible power supply systems (UPS) using electrochemical battery energy storage are very well developed and applied to sensitive loads and in emergency events. Today we face continuous needs of power quality improvement and number loads, required uninterruptible supply, is growing rapidly too. The battery is the source of energy which is delivered to load usually through a DC/AC power electronic converter. A capacity of the battery storage is rated from seconds to hours or even days [6, 18, 21]. Depending on principle of operation there are two main groups of UPS: rotary and static [6, 7, 15, 18–22]. The examples of static UPS are: off-line, line interactive, delta conversion on-line and ferroresonanat. The most common are static UPS's are: off-line, line interactive and on-line [15, 19, 21].

The UPS static energy (battery) storage is heavy and requires high investment funds. Therefore, in case requirement of extended time an additional genset (generating system), made from synchronous generator driven by Diesel engine is applied. This genset is an independent AC source used as replacement of utility [4, 5, 6, 12]. A hybrid UPS (H-UPS) consists of static energy storage, power electronic converter and generation system built as one block commonly controlled. A choice of types of UPS dedicated to hybrid development was preceded by analysis of existing systems. The specified hybrid design has to consist of UPS and modern adjustable speed generation system (VSIG). Figure 1 shows block diagram of simple off-line UPS. In normal conditions the load is powered from utility delivering voltage U_{LINE} through LINE FILTER and TRANSFER SWITCH. An energy storage BAT.STORAGE is charged from the utility through AC/DC converter CONV1. In case of grid failure the TRANSFER SWITCH connects load to DC/AC converter INV and disconnect from supply line. The INV produces AC voltage taking the power from the battery. The TRANSFER SWITCH operation usually results in short break of delivered power.

Figure 2 shows principle of line interactive UPS operation. In presents of utility voltage U_{LINE} the load is supplied via STATIC SWITCH. In case of grid failure the DC/AC converter CONV starts instantly and delivers power from battery to load LD. The action of static switch, made from thyristors, is very short but there is sort of dead time resulted by thyrisitor operation.

There is no any break of the supply power in on-line UPS system shown in Figure 3 [7, 15, 19, 21, 22]. The load LD is supplied always from DC/AC converter INV. In case of presents of utility the CONV1 powers the DC link (U_{DC}) from grid. The battery BAT.STORAGE is pre-charged from the grid via AC/DC converter CONV2. In any events of DC link voltage drop below references a DC/DC converter takes power from battery and supplies the DC link assuring safe operation of the converter INV producing AC voltage delivered to load LD.

The concept of common DC link (U_{DC}) of on-line (double conversion) is very flexible and permits to use more than two power sources. Therefore, this DC link may be supplied

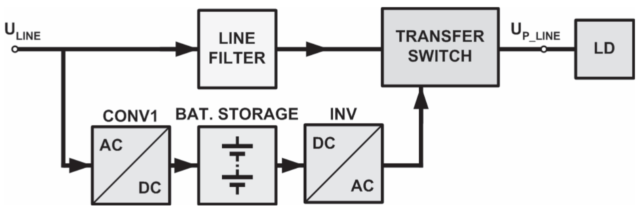


Fig.1. Block diagram of the off-line (standby) UPS system

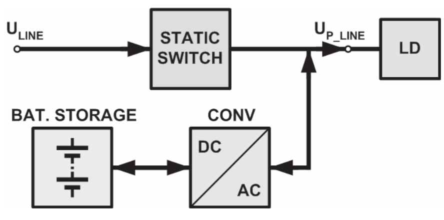


Fig.2. Block diagram of the line interactive UPS system

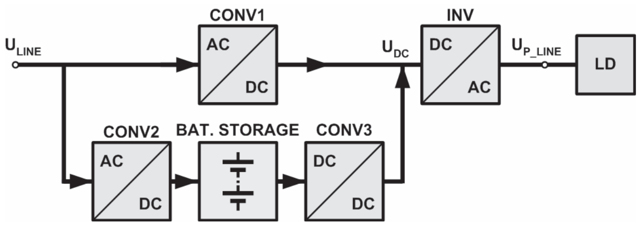


Fig.3. Block diagram of the on-line (double conversion) UPS system

from an additional generation system providing DC link controllable voltage. A permanent magnet generator driven by an internal combustion engine produces variable frequency and amplitude voltage. This voltage is rectified and boosted to the demanded value responding to requirements of an DC/AC converter [1, 8, 9, 10]. There are two options of use of the generation system. In the first, when utility voltage is in range of its rating, the generator operates at lowest speed i.e. it is on-line ready to accelerate following demanded power. In the second the generator is in stand-by state ready to start and supply the DC link. During the start energy is delivered by the static energy storage provided by a supercapacitor. The paper presents hybrid UPS with stand-by generator supplying DC link of the on-line UPS arrangement.

2. HYBRID UPS BASED ON SUPERCAPACITOR ENERGY STORAGE AND ADJUSTABLE SPEED GENERATING SYSTEM

Variable/adjustable speed generation systems is an emerging technique [1, 2, 8, 10, 11, 16, 17] which may be applied to UPS based on power electronic converters. The adjustable speed generating systems operate in the speed range of highest efficiency and assuring long life of the Diesel engine. Another emerging technique is supercapacitor energy storage which has feasibility to compete, in low capacity demands. An important advantage of the supercapacitor is ability to provide high current in both charging and discharging circumstances [2, 8, 9, 25]. Moreover, the deep discharge does not damage the capacitor [25]. The number of advantages of the supercapacitor application is still under investigation [2, 8, 9].

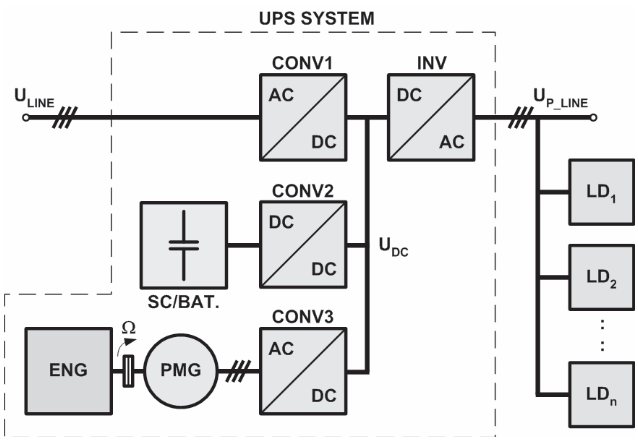


Fig.4. Block diagram of the proposed hybrid on-line UPS system

Figure 4 shows block diagram of the developed Hybrid UPS (H-UPS). It consists blocks of on-line UPS with DC link voltage supplied from AC/DC by a converter CONV1 from the utility and from an energy storage SC/BAT via reversible DC/DC converter CONV2. A DC/AC converter INV produces standard AC voltage U_{P_LINE} demanded by set of loads, LD_1, LD_2, … LDn. For laboratory purpose, as CONV1 was applied six pulse rectifier. For modern commercial application should be considered active rectifier to achieve low THD of line current [14].

The DC link voltage is U_{DC}. To the DC link is connected the adjustable speed generating system which consists of driving engine ENG, permanent magnet generator PMG and AC/DC converter CONV3. The AC/DC converter CONV3 has to deliver the power to UPS DC link in case of drop of the U_{DC} voltage below a reference level or in other event coming from H-UPS strategy of control.

The laboratory three phase hybrid H-UPS was built according a block diagram shown in Figure 5. The DC link of the H-UPS is supplied from utility via transformer TR1 and rectifier CONV1, from permanent magnet generator PMG via rectifier CONV3-1 and a DC/DC booster CONV3-2 and from the supercapacitor SC through switch SP_{SC} and reversible DC/DC converter CONV2. The axial flux permanent magnet generator is driven by prime mover ENG. The H-UPS is controlled by DSP control unit system CONT. A three phase load LD have to be protected against utility voltage U_{LINE} failure. The utility is basic source of power. The autotransformer TR1 represents grid which supplies load LD via converter rectifier CONV1 and DC/AC converter INV. The power delivered/absorbed by the supecapacitor energy storage (CESS) is controlled by DC/DC converter CONV2 through control of discharging ($I_{SC\_DSISCHAR\_REF}$) and charging (I_{SC_CHAR}) current:

$$P_{SC}(t) = I_{SC}(t)U_{SC}(t) \qquad (1)$$

where:

I_{SC}, U_{SC} — are current and voltage of the supercapacitor bank.

Maximum available power is:

$$P_{SC\_MAX} = I_{SC\_DISCHAR\_REF}\, U_{SCref0} \qquad (2)$$

where:

U_{SCref0} — is rated voltage of the supercapacitor bank

$I_{SC\_DSISCHAR\_REF}$ — is reference value of the charging current.

The adjustable speed generation system delivers DC current to the DC link and generator rectifier current I_{dg} is controlled by the DC/DC converter CONV3-2 [1, 2, 8, 11, 17]. There are two states of the adjustable speed generation system operation: first is related to dynamic state of speed variation and second — steady state with constant speed responding given power demand. The control of the generator rectified current I_{dg} permits to control load torque T_L produced by he generator:

$$T_L(t) = K_{dg}\, I_{dg}(t) \qquad (3)$$

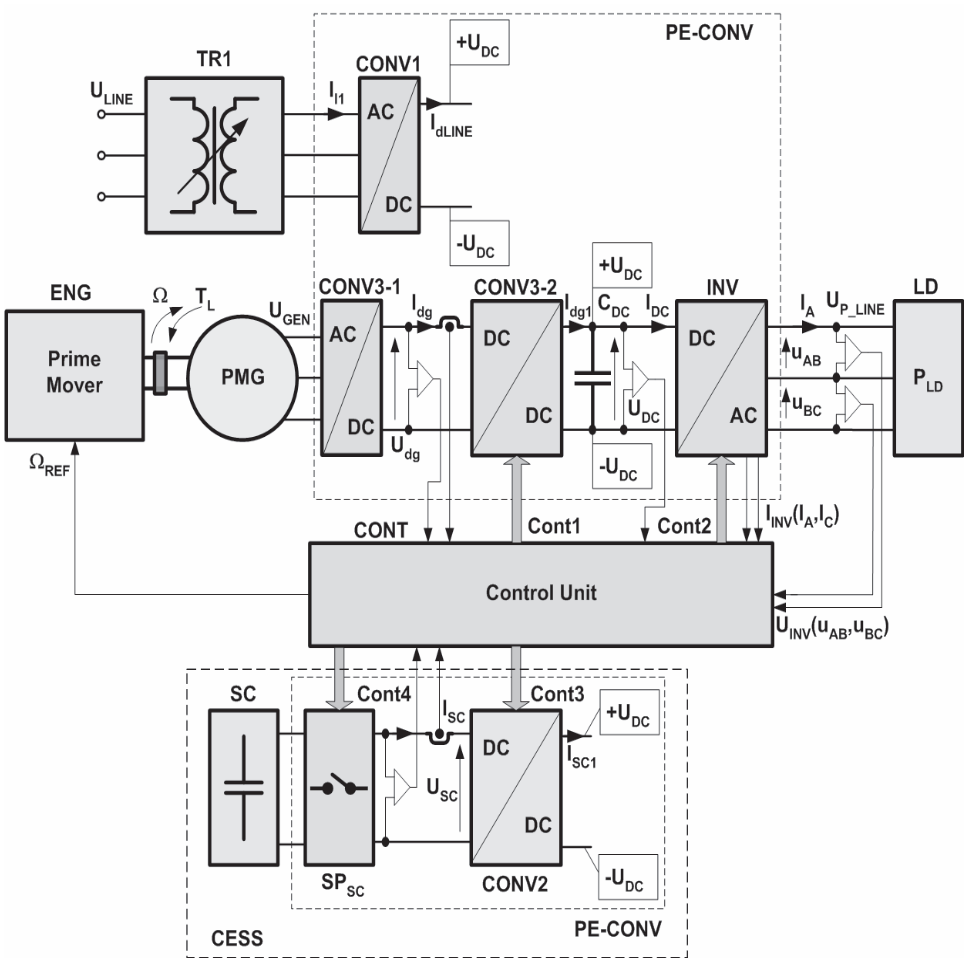


Fig.5. Block diagram of the laboratory hybrid on-line UPS system. Application of supercapacitor energy storage and variable speed generating system

where K_{dg} is factor of equivalent linkage flux.

As result of control I_{dg} current (then load T_L), there is possibility to control performance of driving engine (speed, acceleration):

$$\Omega(t) = f(T_D, T_L, J, \Omega_0) \quad (4)$$

where:

T_D — is drive torque,
J — is moment of inertia (engine and generator, Ω_0 is initial speed).

According to control of generator current I_{dg} (load torque T_L) and speed (Ω) there is way to control power generated by driving engine (ENG), which can be generally described as:

$$P_{dg}(t) = \Omega(t)\, T_L(t) = K_{dg}\, I_{dg}(t)\, \Omega(t) \quad (5)$$

3. STRATEGY OF CONTROL OF THE HYBRID UPS SYSTEM BASED ON SUPERCAPACITOR ENERGY STORAGE AND VARIABLE SPEED GENERATING SYSTEM

Strategy of the on-line UPS operation is based on monitoring of DC link voltage. AC supply voltage (U_{LINE}) variation or failure, sudden increase of the load results in the DC link voltage U_{DC} drop. When the DC link voltage decreases to a given reference U_{DCref1} (Fig. 6) that is symptom of lack of supply power and then the controlled energy storage is ordered to support the DC link. In case of hybrid system H-UPS there are two potential energy sources that can support the DC link voltage. Hence, a different strategy of the DC link voltage is needed. Therefore, developed method is based on DC link voltage U_{DC} compared to the reference level, DC voltage changes $\Delta U_{DC}/\Delta t$, difference of the supercapcitor voltage U_{SC} to initial voltage, dynamics

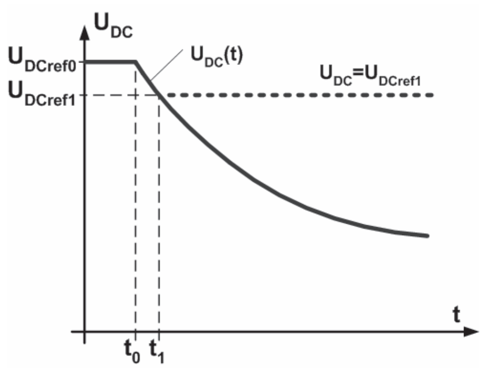


Fig.6. Example of simple method control of controlled energy storage system (BAT.STORAGE) in on-line UPS system. Relationship between time of activating controlled energy storage (t_1) and U_{DC} voltage drop (U_{DCref1}) caused by power line voltage deep (U_{LINE})

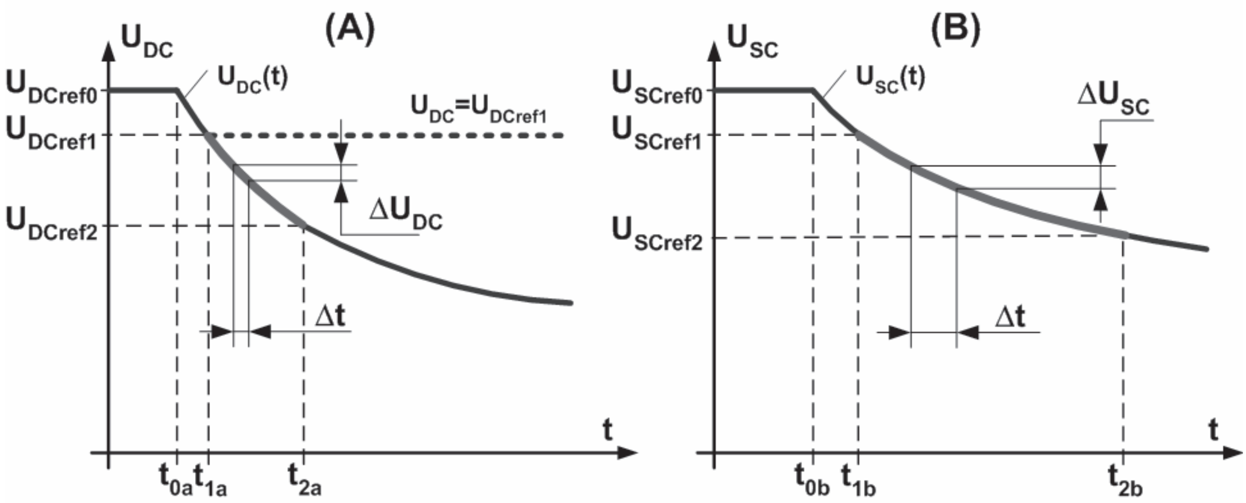


Fig.7. Strategy of activating CESS and Generating System (ENG+PMG) in Hybrid UPS system. Signals: $U_{DC}(t)$, $\Delta U_{DC}/\Delta t$, $U_{SC}(t)$ and $\Delta U_{SC}/\Delta t$ controlled in Hybrid UPS during operation caused by power line voltage deep (U_{LINE}). Strategy: $U_{DC}<U_{DCref1}$ — activating CESS (t_{1a}), $U_{DC}<U_{DCref2}$ or $(\Delta U_{DC}/\Delta t)>K\Delta U_{DCref}$ or $U_{SC}<U_{SCref2}$ or $(\Delta U_{SC}/\Delta t)>K\Delta U_{SCref}$ — activating Generating System (ENG+PMG).

changes of supercapacitor voltage $\Delta U_{\mathrm{SC}}/\Delta$t. An analysis of the above data provides time sequence of the supporting energy sources: sueprcapacitor system CESS and adjustable speed generation system: ENG, PMG, with CONV3-1 and CONV3-2 (Fig. 5).

Short breaks of supply voltage U_{LINE} results in operation of the supercondensator controlled storage whereas the adjustable speed system is starting when the energy stored in the CESS is below given reference level. The internal combustion as for instance Diesel engine requires time ($\Delta T_{\mathrm{START\text{-}ENG}}$) to start and to be warmed. The energy storage CESS is sized to keep the DC link voltage, during starting process of the genset on reference level.

Figure 7 shows DC link voltage U_{DC} (Fig. 7A) and supercapacitor voltage (Fig. 7B) as function of time in case of failure of the supply voltage U_{LINE}. The strategy of the H-UPS control is based on following references shown in Figures 7A and 7B:

— U_{DCref0} — U_{DC} voltage responding rated AC supply line voltage,

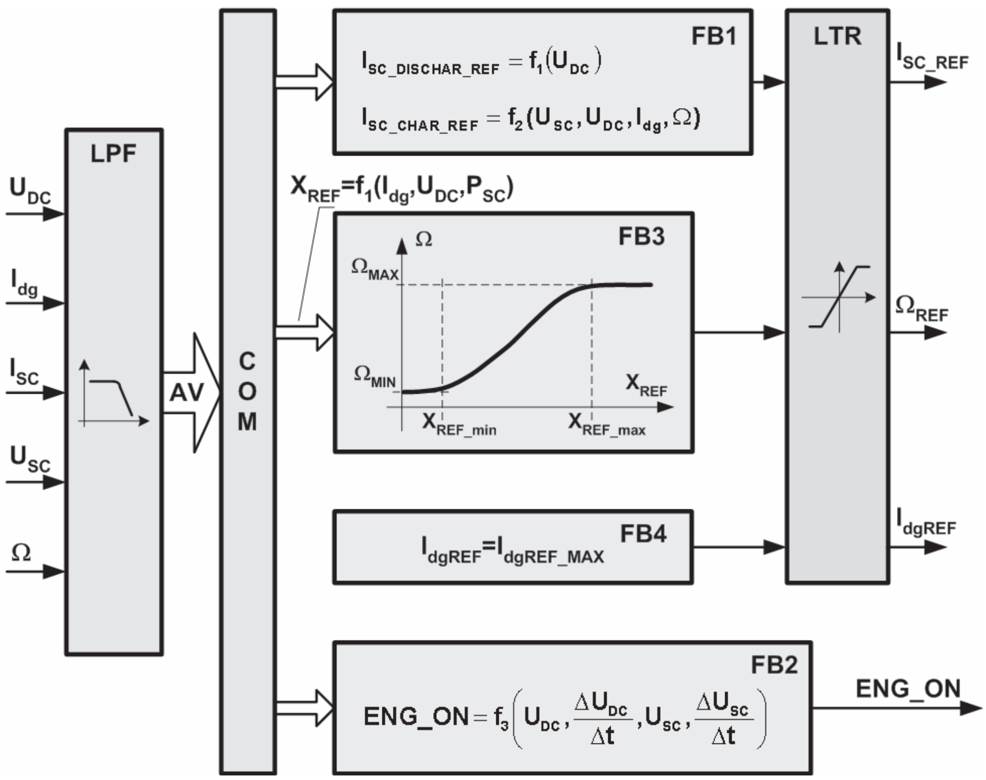


Fig.8. Block diagram of the part of the control system implemented in laboratory hybrid on-line UPS system. Computing reference signals: I_{SC_REF}, I_{dg_REF}, Ω_{REF} and engine activating signal – ENG_ON, where: LPF – low pass filters, COM – computation module, LTR – limiters, FB1.FB4 – function blocks (computing: $I_{\mathrm{SC\_DISCHAR\_REF}}$, $I_{\mathrm{SC\_CHAR\_REF}}$, ENG_ON, Ω_{REF}, I_{dgREF}).

— U_{DCref1} — below this value of the U_{DC} voltage energy storage CESS is applied to maintain the DC link voltage
— U_{DCref2} — below this level starts engine ENG
— For range $U_{DCref1} > U_{DC} > U_{DCref2}$ and $\Delta U_{DC}/\Delta t > K\Delta_{DCref}$ starts the ENG too, where: $\Delta U_{DC} = U_{DC}(n-1) - U_{DC}(n)$, $(n-1)$, (n) mean previous and current sample, and $K\Delta_{DCref}$ is reference value.

The energy storage voltage variation is also considered in the system control and following references are applied:
— U_{SCref0} — rated voltage of the supercapacitor SC
— U_{SCref2} — below this voltage the engine starts
— For range $U_{SCref1} > U_{SC} > U_{SCref2}$ and $\Delta U_{SC} / \Delta t > K\Delta_{SCref}$ starts engine ENG, where: $\Delta U_{SC} = U_{SC}(n-1) - U_{SC}(n)$, $(n-1)$, (n) mean previous and current sample and $K\Delta_{SCref}$ is reference value.

In the while of starting the generator does not produces power and then the engine accelerates to minimum speed in a very short time. After the time $\Delta T_{START\text{-}ENG}$ it start accelerate gradually and begin to produce a power and when is fully warmed it produce full demanded power. There is also option to quick charge the supercapcitor (SC) to its reference voltage. Supercapacitor charging current (I_{SC_CHAR}) depends on a current state of the UPS system:

$$I_{SC\_CHAR} = f(U_{SC}, U_{DC}, I_{dg}, \Omega) \qquad (6)$$

At the end of the starting event and charging supercapaitor the speed of the genset (Ω_{REF}) is depending on load P_{LD}. The power drawn from the generator is proportional to the generator rectified current I_{dg} and a reference speed factor K_{REF}:

$$\Omega_{REF} = f(P_{LD}) = f(K_{REF}\, I_{dg}) \qquad (7)$$

In case of short break of power only supercapacitor is source of power and in while of return of grid power the supercapacitor is instantly charged, just to be ready for next cycle. Figure 8 shows block diagram of the H-UPS control system, whereas Figure 9 presents control algorithm implemented in the laboratory system.

An example illustrating the H-UPS system operation sequence during supply voltage break (U_{LINE}) is showed on Figure 10. According to Figure 10, H-UPS system is loaded by P_{LD} load. Grid voltage (U_{LINE}) break (t_0) causes DC link voltage dip (U_{DC}). After t_1 — activated Controlled Energy Storage System (CESS) produces P_{SC} power to supply load. On base of U_{SC} measured value (amount of energy stored in SC) Control Unit starts engine on (ENG – t_2), after time necessary to warm-up engine (ΔT_{START_ENG}, t_3) engine is switched to load (LD) and produces power (P_{dg}) proportional to speed (5). After time t_4, supercapacitor energy storage (CESS) is switched off. Load (LD) is then supplied only by Variable Speed Generating System (ENG+PMG). Because load (P_{LD}) is lower than possible maximum generating power (P_{dgMAX}), after time t_5 supercapacitor charging process is activated.

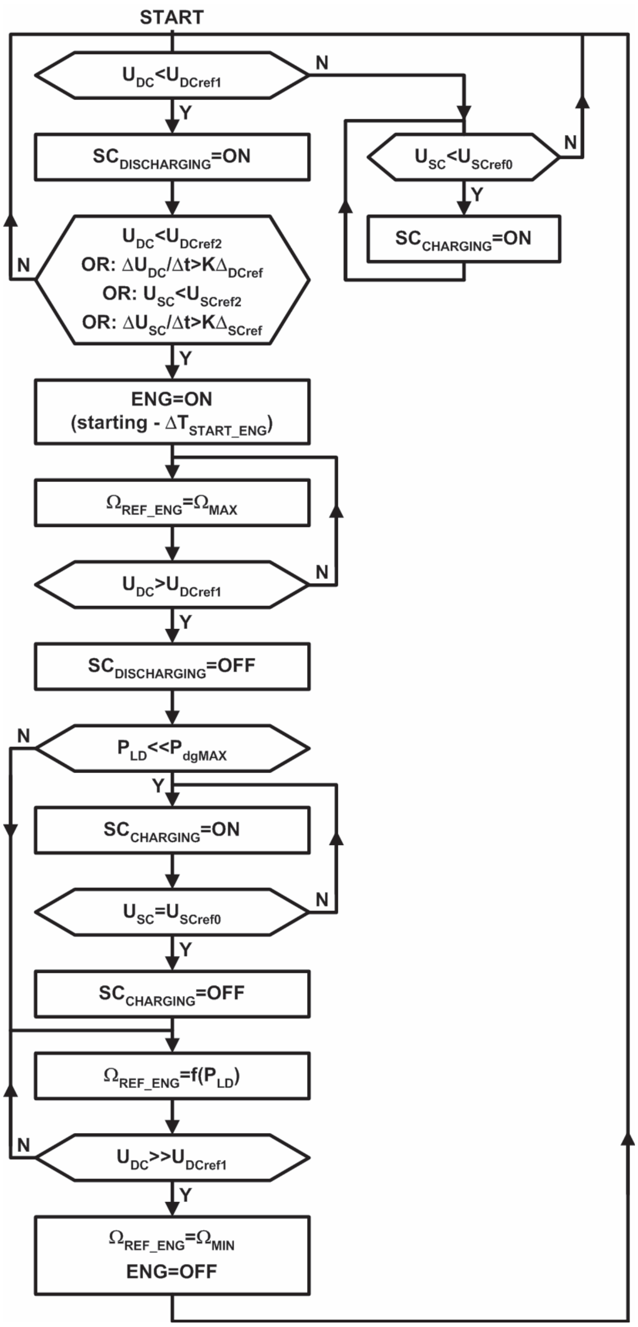


Fig.9. Algorithm of the control strategy of the laboratory hybrid UPS system (Y—yes, N—No, $SC_{DISCHARGING}$ = ON — CESS is activated, ENG = ON — engine is switched on, ΔT_{START_ENG} — time for engine starting and warming up, $SC_{CHARGING}$ = ON — process of SC charging is activated).

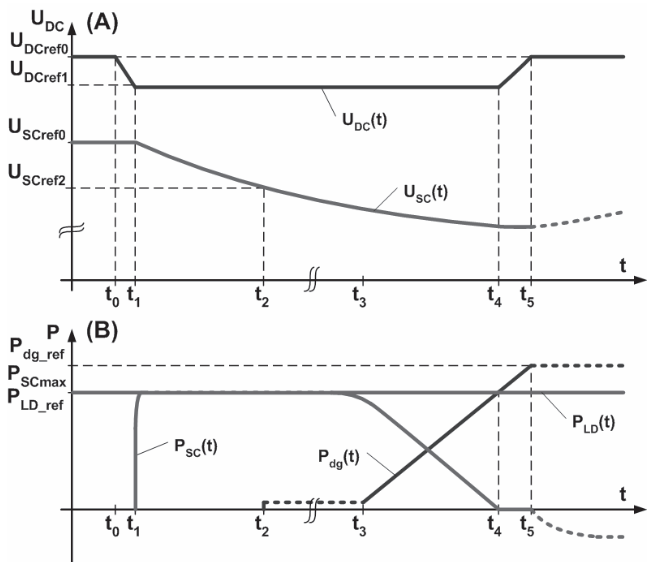


Fig.10. An example of Hybrid UPS operation caused by lost U_{LINE} supply (t_0). UPS system is loaded by P_{LD} load. Activating of Controlled Energy Storage System (CESS – t_1) – CESS unit produces P_{SC} power. On base of U_{SC} measured value (amount of energy stored in SC) Control Unit starts engine on (ENG – t_2), after time necessary to warm-up engine (ΔT_{START_ENG}, t_3) engine is switched to load (LD) and produces power proportional to speed (P_{dg}). After time t_4, CESS is switched off and all power produces Variable Speed Generating System. Because P_{LD} is lower than P_{dgMAX}, after time t_5, there is possibility to charge SC by Generating System (ENG+PMG).

4. BASE REQUIREMENTS FOR CONTROLLED ENERGY STORAGE SYSTEM (CESS) IN H-UPS SYSTEM

An energy which may be delivered by the DC link to the load is depending on its capacity C_{DC} and difference of voltages:

$$\Delta E_{CDC} = \frac{C_{DC}}{2}\left(U_{DCref0}^{2} - U_{DCref1}^{2}\right) \tag{8}$$

where U_{DCref0} is initial voltage and U_{DCref1} is a reference value which activates superacapacitor energy storage (CESS). In some range level of the U_{DCref1} value depends on considered energy (ΔE_{CDC}) which can be drawn from capacity C_{DC}:

$$U_{DCref1} = f(\Delta E_{CDC}) \tag{9}$$

The minimum of the DC link capacitor voltage U_{DCref2} is the lowest voltage which permits to produce by the DC/AC inverter (INV) demanded AC (U_{P_LINE}), then it can be described as a function of minimum accepted inverter voltage $U_{DC\_INV\_MIN}$:

$$U_{DCref2} = f(U_{DC\_INV\_MIN}) \tag{10}$$

In practice the capacity of the DC link electrolytic capacitors is low and they mainly smooth DC link voltage during transients and grid short disturbances.

Main source of power, providing in the begin of the lack of the utility (U_{LINE}), is supercapcitor energy storage CESS.

The available energy from the supercapacitor depends on its capacity C_{SC} and its voltages: initial U_{SCref0} and at the end of discharging U_{SCmin}:

$$\Delta E_{SC} = \frac{C_{SC}}{2}\left(U_{SCref0}^{2} - U_{SCmin}^{2}\right) \tag{11}$$

The supercapcitor has to deliver full demanded, by load, power (in case when power delivered by grid (P_{LINE}) and generating system (P_{dg}) are zero):

$$P_{SC}\,(P_{LINE} = 0, P_{dg} = 0) = P_{LD} \tag{12}$$

and then energy (for constant load power):

$$E_{SC}\,(\Delta t_{DISCHAR}) = P_{SC}\,\Delta t_{DISCHAR} = P_{LD}\,\Delta t_{DISCHAR} \tag{13}$$

where $\Delta t_{DISCHAR}$ is a time when energy storage (CESS) is activated.

Reference value U_{SCref2} at which driving engine (ENG) is started can be described as function (14). Due to equation (11) and (13) U_{SCref2} reference value can be described (15). In (15) $\Delta t_{DISCHAR}$ is treated as a total time when energy storage (CESS) is activated – this time also include time ($\Delta T_{START\text{-}ENG}$) which is necessary to start and warm up driving engine (ENG):

$$U_{SCref2} = f\left(P_{LD}, \Delta t_{DISCHAR}, U_{SCmin}, C_{SC}\right) \tag{14}$$

$$U_{SCref2} \geq \sqrt{\frac{2P_{SC}\Delta t_{DISCHAR}}{C_{SC}} + U_{SCmin}^{2}} \tag{15}$$

On the base of a speed of supercapacitor discharging ($\Delta U_{SC}/\Delta t$) Control Unit can turn the engine (ENG) on. Reference value of a speed of SC discharging $K\Delta_{SCref}$ can be described as:

$$K\Delta_{SCref} = K_{\Delta SC}\frac{U_{SCref0} - U_{SCmin}}{\Delta t_{DISCHAR}} \tag{16}$$

where $K_{\Delta SC}$ is frequency sampling factor.

According to equation: (11, 12, 13), there is possibility to determine time $\Delta t_{DISCHAR}$ as a function of load (P_{LD}) and U_{SC} voltage:

$$\Delta t_{DISCHAR} = \frac{C_{SC}}{2P_{LD}}\left(U_{SCref}^{2} - U_{SCmin}^{2}\right) \tag{17}$$

Figure 11 shows recovery time as a function of load power and minimum supercapacitor voltage $\Delta t_{DISCHAR} = f\,(P_{LD}, U_{SCmin})$ for the system data: C_{SC} = 50F, U_{SCref0} = 100V, U_{SCmin} = 20..80V, P_{LD_MAX} = 5kW. The presented range of time is inside of 120s, what is typical starting time for driving engine (Diesel engine).

Figure 12 shows required capacity of the energy storage SC as a function of load power P_{LD} and reference time of voltage recovery $C_{SC} = f(P_{LD}, \Delta t_{DISCHAR})$ for following data: U_{SCref0} = 100V, U_{SCmin} = 50V, P_{LD_MAX} = 5kW.

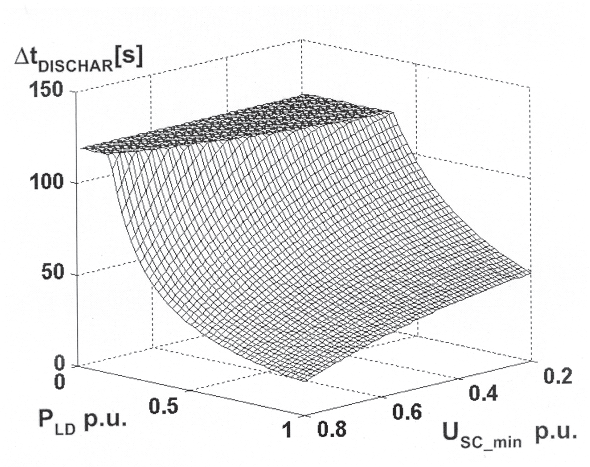


Fig. 11. An example of allowed time ($\Delta t_{DISCHAR}$), in which CESS unit is activated and can supply load (LD), as a function of load (P_{LD}) and allowed SC discharging level for C_{SC} = 50F. Parameters: P_{LD_MAX} = 5kW, U_{SCref0} = 100V, $U_{SC\min}$ = 80..20V. On the characteristic time ($\Delta t_{DISCHAR}$) was limited to 120s (typical time to warm up Diesel engine)

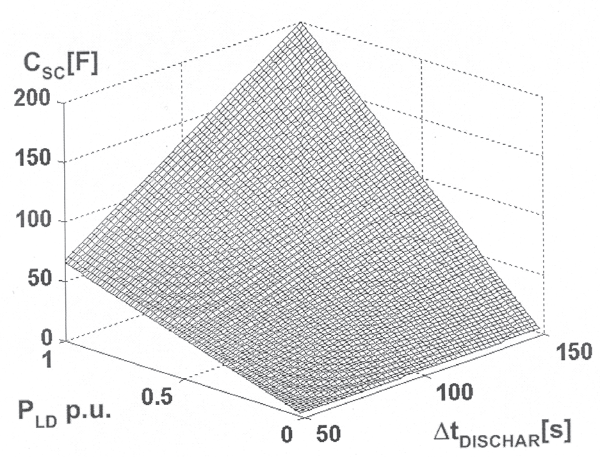


Fig. 12. An example of required SC capacity (for CESS) as a function of load (P_{LD}) and time of activating CESS ($\Delta t_{DISCHAR}$). Parameters: P_{LD_MAX} = 5kW, U_{SCref0} = 100V, $U_{SC\min}$ = 50V

5. LABORATORY MODEL OF THE HYBRID UPS SYSTEM

The laboratory model of the H-UPS responding to block diagram from Figure 5, was built and tested. Figure 13 shows the H-UPS converters, load bank and a line transformer (PE-CONV: CONV1, INV, CONV2, CONV3; LD; TR1).

The supercapacitor energy storage SC (topology shown in Figure 14) is presented on the Figure 15. As the prime mover was used DC motor controlled by thyristor converter TCONV (Fig. 16). The application of DC motor, with fully controlled dynamics and speed range, permits to tests in laboratory conditions driving systems responding different types of engines. As the generator PMG is used modern axial flux permanent magnet 16 poles machine [1, 2, 8, 17, 24] (Fig. 17 and 18).

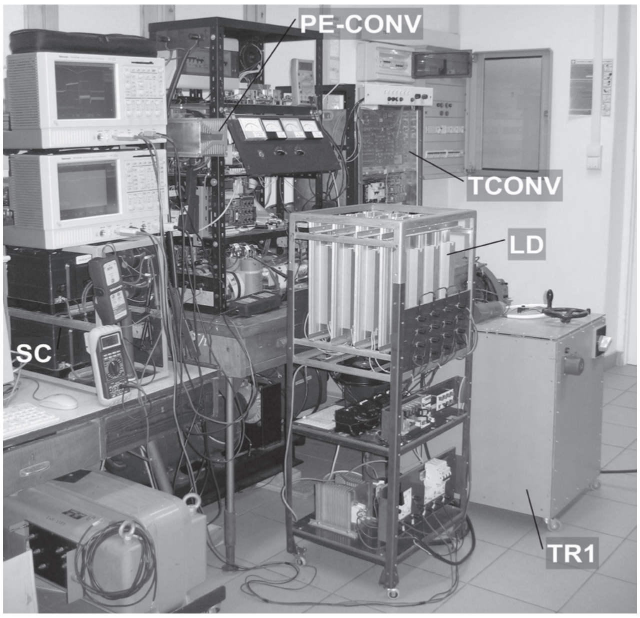


Fig. 13. Hybrid UPS system – Line Transformer (TR1), powerelectronics converters PE-CONV (CONV1 – AC/DC converter, INV – three phase inverter, CONV2 – bidirectional DC/DC converter, CONV3 – AC/DC converter), DSP controller, supercapacitor bank (SC) and resistor load bank (LD)

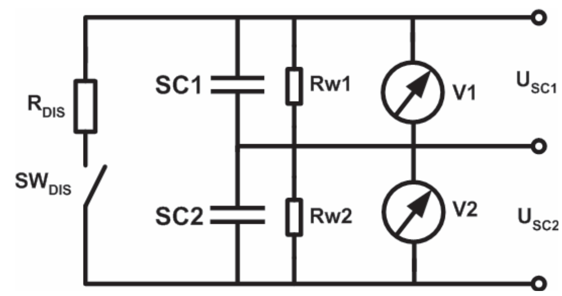


Fig. 14. Supercapacitor energy storage (SC) – series connection of 2 supercapacitors

Fig. 15. Energy storage – supercapacitor bank (SC)

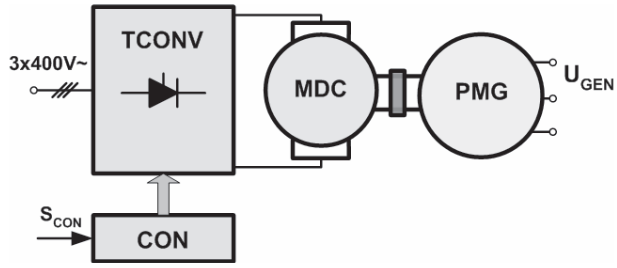


Fig. 16. The DC motor controlled by thyristor converter as simplified laboratory model of the internal combustion driving engine

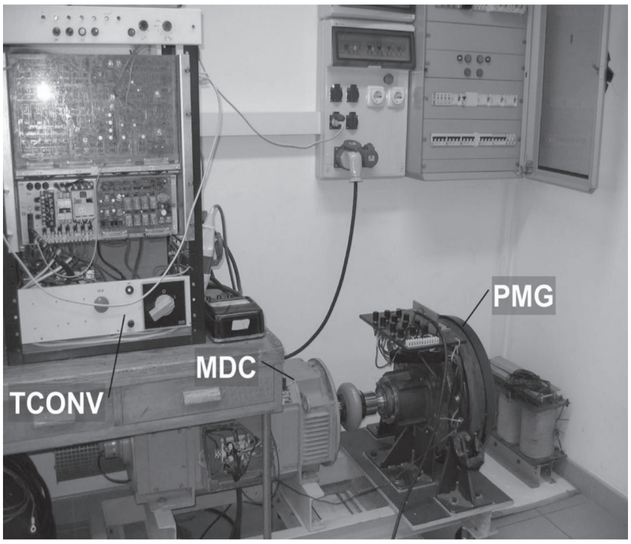


Fig. 17. Laboratory model of the driving engine – blocks: MDC - DC motor, TCONV - thyristor converter and PMG - permanent magnet generator

Fig. 18. PMG – Axial Flux permanent magnet generator

The generating system controller and all blocks operation (Fig. 5) was designed and preliminary tested using simulation program PSIM 6.0 [13, 26]. The control system was implemented using C++ Builder [23]. The controller (Fig. 8) was built using DSP processor Analog Devices Sharc 21061 with support of ALTERA EPF6016 [3, 13]. Data of the built laboratory H-UPS are shown in Table I and Table II.

Table 1. Data of the laboratory test system

Component	Data
TR1	3 Phase Autotransformer Pn =5kVA
CONV1	• Three phase bridge rectifier
Three phase inverter (INV)	• Output AC voltage: U_{INV_RMS} = 115[V], f = 50[Hz]; • Output filter data: L_{INV} = 0.7[mH], C_{INV} = 250[μF]; • Switching frequency – fs = 16[kHz];
CESS – Super capacitor SC	• EPCOS B48720-G7674-Q018, • C_{SC} = 67[F], U_{SC} = 42[V], • Passive compensation, • Parameters – serial connection: C_{SC} = 33.5F/84V
CESS – DC/DC converter (CONV2)	• DC link voltage which activates energy transfer from SC storage to DC link – U_{DC} = 190[V]; • Supercapacitor bank SC reference voltage – U_{SC} = 75[V], • Reference max. discharging current of the supercapacitor bank – $I_{SC-DISCHAR-MAX}$ = 50[A]; • Reference max. SC bank charging current – $I_{SC-CHAR-MAX}$ = 40[A]; • Choke inductance – L_{DC} = 1[mH]; • Switching frequency – fs = 16[kHz];
Engine model (ENG)	• Rated power of the DC Motor – PN = 18[kW]; • DC motor coefficient – K_{MDC} = 2.9 [Nm/A]; • Max. power of the prime mover limited to - P_{ENG} = 9[kW]; • Total inertia factor of the prime mover and permanent magnet generator – J = 0.95[kgm2]; • Minimum and maximum speed – Ω_{min} = 50[rad/s], Ω_{max} = 150[rad/s]; • Max. drive torque of the prime mover limited to - T_{max} = 60[Nm];
Permanent Magnet Generator (PMG)	• PMG voltage factor – K_{GEN} = 0.06 [Vs/rad]; • Number of pole pairs – p = 8; • PMG phase R and L – R = 80[mΩ], L = 70[μH];
CONV3-1	•Three phase bridge rectifier
DC/DC Converter (CONV3-2)	• DC link voltage – U_{DC}=200..250[V]; • Max. PMG rectified current limited to – I_{dgMAX} = 45[A]; • Choke inductance (step-up chopper) – L_{DC} = 1[mH]; • DC link capacitance – C_{DC} = 8[mF]; • Switching frequency – fs = 16[kHz];
Load (LD)	• Resistive load 0 – 5kW („Δ" – connection); • 12 resistors, total dissipative power – P_{MAX} = 5kW
Control Unit of the all System (CONT)	• Control system is based on the DSP SHARC 21061 Analog Devices processor and programmable unit ALTERA EPF6016.

6. LABORATORY TESTS OF THE H-UPS

The laboratory experiments were provided to tests the H-UPS output voltage in case of supply voltage failures. There were used 2 scopes measuring signals (settings):

— Scope I: ch1: U_{DC} (50V/div), ch2: I_{dLINE} (20A/div), ch4: U_{P_LINE} (50V/div);
— Scope II: ch1: U_{SC} (50V/div), ch2: I_{SC} (20A/div), ch3: Ω (33rad/s), ch4: I_{dg} (20A/div);
— ΔT = 5s/div (Fig. 17, 18), 10s/div (Fig. 19, 20), 2ms/div (Fig. 25);

Tabela 2. Data of the reference signals

Signal	Value
U_{DCref0}	>200V (max. 250V)
U_{Dcref1}	190V
U_{Dcref2}	170V
$K\Delta_{Dcref}(U_{DC}/\Delta t)$	>50V/s
US_{Cref0}	75..78V
U_{Scref1}	73V
U_{Scref2}	67V
$K\Delta_{SCref}(U_{SC}/\Delta t)$	>1V/s
ΔT_{START_ENG}	10s (short time for laboratory tests)

A. Test 1 – Short break of the supply voltage

Figures 19 and 20 show result of tests during short break (about 7 sec) of the supply power. The Figure 19 shows output AC voltage U_{P_LINE} and DC link voltage U_{DC} in case of power supply break – gap in the rectified line current I_{dLINE}. The H-UPS is loaded with 2.5 kW. The supply break (t_0) is instantly followed by supercapacitor current I_{SC} (Fig. 20) which maintain the DC link voltage U_{DC} in range permitting to keep the AC voltage (Fig. 19) without any changes. The supercapacitor discharging current I_{SC} results in the supercapacitor voltage U_{SC} drop. However, just after return of the supply voltage (while t_2) the supercapacitor is recharged and then, in about 15s, the supercapacitor voltage recoveries is rated value (t_3).

B. Test 2 – Long break of the supply voltage (case 1)

Results of long break supply voltage tests of the H-UPS system operation are shown in Figures 21 and 22. The H-UPS is loaded by 2.5 kW. The cut of the supply power (Fig. 21) results in quick rise of the supercapacitor current I_{SC} (Fig. 22). In the first instant the DC link voltage U_{DC} is kept constant on its reference value related to operation in disturbances. As the supercapcitor current is limited then, due its discharge, the delivered power drops and the DC link voltage U_{DC} and AC output voltage drops too (Fig. 21). At the time $t = t_1$ the engine (ENG) starts ($\Delta T_{START\_ENG} = 10s$ is required to warm up, during this time engine runs at minimum speed $\Omega = 50rad/s$). During acceleration and further between t_2 and t_3 the generator (PMG), according to control strategy, does not delivers power (P_{dg}) and the DC link voltage and then AC voltage (U_{P_LINE}) is going down. However, the AC voltage drop is not significant. At the $t = t_3$ (Fig. 22) the generating system accelerates again (to the reference speed Ω_{REF}) and starts to deliver power. The reference speed is high to meet all needs of load and charging. The DC link voltage U_{DC} recovers its reference value by charging DC link capacitor C_{DC}. From $t = t_3$ generating system starts charging supercapacitor storage SC (current I_{SC}). Since the

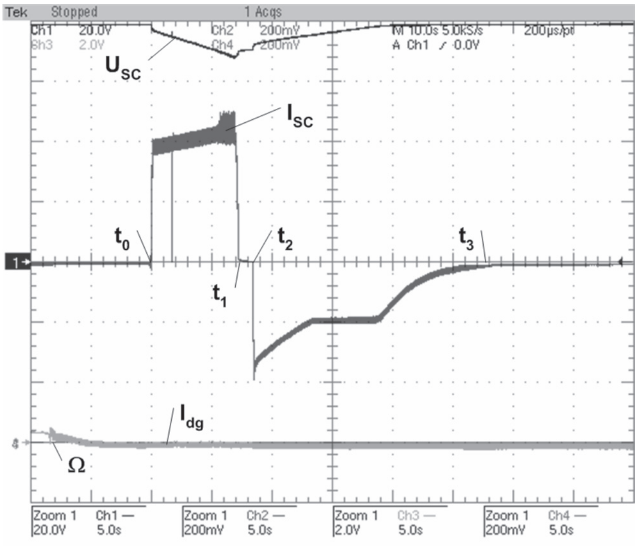


Fig. 20. Laboratory test of the Hybrid UPS system – test1 (U_{SC}, I_{SC}, Ω, I_{dg}). Laboratory Hybrid UPS operation during short time power supply break. Operation of Controlled Energy Storage System (CESS): discharging, charging

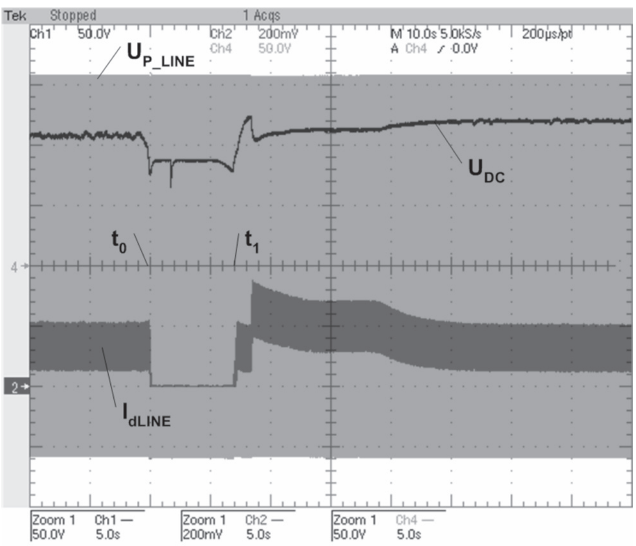


Fig. 19. Laboratory test of the Hybrid UPS system – test1 (U_{DC}, I_{dLINE}, U_{P_LINE}). Laboratory Hybrid UPS operation during short time power supply break. Operation of Controlled Energy Storage System (CESS): discharging, charging

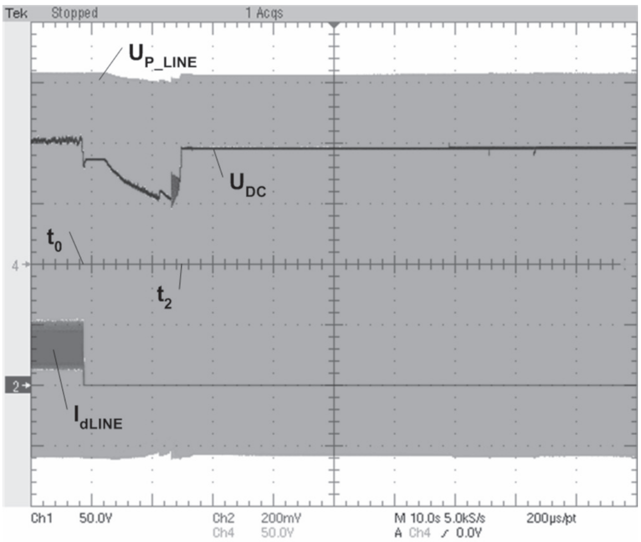


Fig. 21. Laboratory test of the Hybrid UPS – test2 (U_{DC}, I_{dLINE}, U_{P_LINE}). Laboratory Hybrid UPS operation during long time power supply break. Operation of Controlled Energy Storage System (CESS) and Variable Speed Generating System (generating system activated by low U_{SC} value)

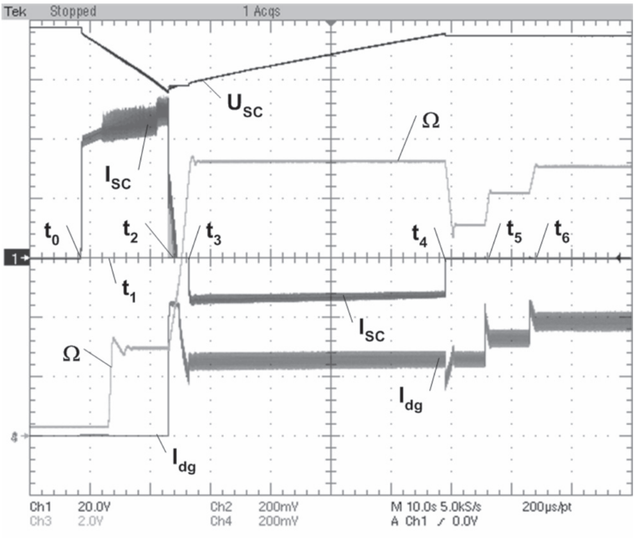


Fig. 22. Laboratory test of the Hybrid UPS – test2 (U_{SC}, I_{SC}, Ω, I_{dg}). Laboratory Hybrid UPS operation during long time power supply break. Operation of Controlled Energy Storage System (CESS) and Variable Speed Generating System (generating system activated by low U_{SC} value)

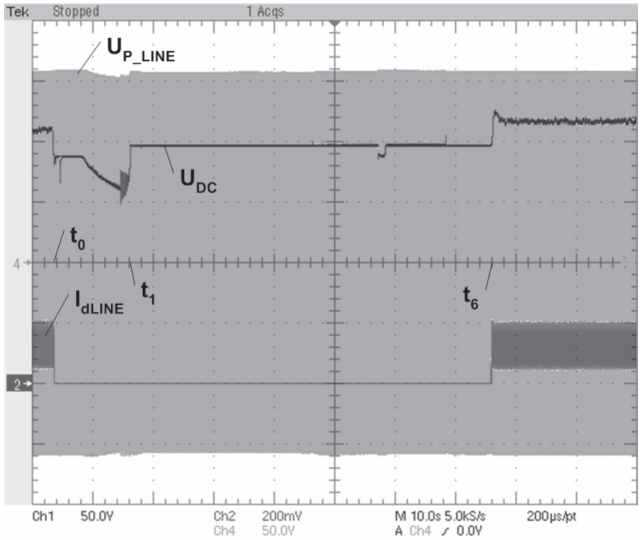


Fig. 23. Laboratory test of the Hybrid UPS – test3 (U_{DC}, I_{dLINE}, U_{P_LINE}). Laboratory Hybrid UPS operation during long time power supply lost. Operation of Controlled Energy Storage System (CESS) and Variable Speed Generating System (generating system activated by high $\Delta U_{DC}/\Delta t$ ratio).

$t = t_4$ the supercapcitor is recharged too. As its capacitance is very big then it takes about 45s to get its reference value. At the $t = t_4$ begin operation of the H-UPS with adjustable speed generating system as only source of power. Since the supercapcitor is charged the speed of the generating system is reduced to the value responding 2.5 kW load. At $t = t_5$ the load is rising from 2.5 kW to 3.75 kW and the speed is adequately rising. At $t = t_6$ load steps to 5 kW and engine speed is increased again. According to project specification and control concept the AC output voltage U_{P_LINE} drops in steady state of the generating system operation is inside of 5%. Presented test did not consider line voltage (U_{LINE}) return.

C. Test 3 – Long break of the supply voltage (case 2)

Another case of Hybrid UPS system operation during long break of the supply voltage (U_{LINE}) shows Figures 23 and 24. In this case rapid break ($t = t_0$) of power supply (gap in the rectified line current I_{dLINE}) causes immediately reaction of the supercapacitor energy storage (CESS – discharging current I_{SC}). CESS supplies protected load during time $t_0 - t_1$ (P_{LD} = 2.5kW).

Because of rapid character of the transient state (high $\Delta U_{DC}/\Delta t$ ratio) control unit immediately activates generating system. During time t_0–t_1 engine starts and warm up (ΔT_{START_ENG} = 10s, time required to prepare engine to normal work, during this time engine runs at minimum speed Ω = 50rad/s). After time $t = t_2$ the generating system is able to supply load and to charge supercapacitor energy storage, this process takes approximately 28s (t_2–t_3). According to speed control strategy, engine speed is proportional to load, i.e. to rectified generator current (I_{dg}).When power delivered to load changes from 2.5kW to 5kW (t_4) the engine speed increases too (to its maximum value). During acceleration time (about 2s) CESS supports generating system by supplying the load. After time t_5 power delivered to load decrease to 2.5kW.

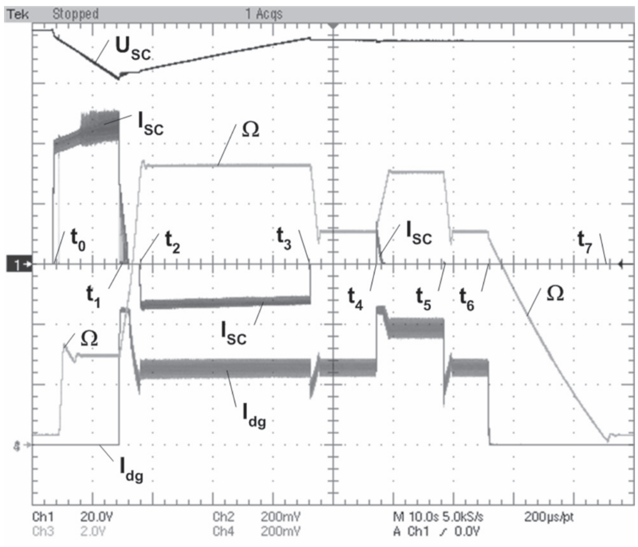
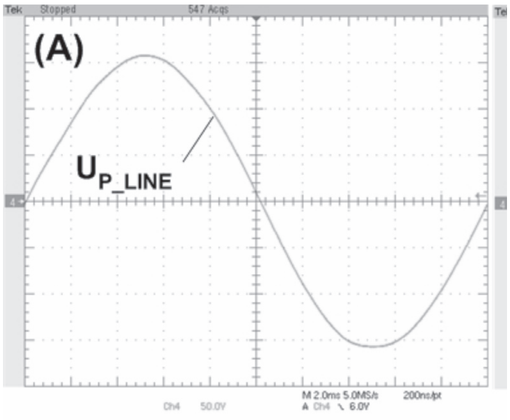


Fig. 24. Laboratory test of the Hybrid UPS – test 3 (U_{SC}, I_{SG}, Ω, I_{Idg}). Laboratory Hybrid UPS operation during long time power supply lost. Operation of Controlled Energy Storage System (CESS) and Variable Speed Generating System (generating system activated by high $\Delta U_{DC}/\Delta t$ ratio).

At $t=t_6$ line voltage (U_{LINE}) is recovered to its nominal value, from this time the load is supplied from the grid. Control unit brakes the engine and after time $t=t_7$ the generating system is switched off. In this case AC output voltage U_{P_LINE} drop in transient state operation is inside 3% of the nominal value. All operations of H-UPS system, caused by line voltage (U_{LINE}) break, take about 74s.

D. Test 4 – Output voltage U_{P_LINE} during steady states

Figure 25 shows AC output voltage (one phase) produced by the H-UPS for a case of idle (A) and 5 kW load (B).



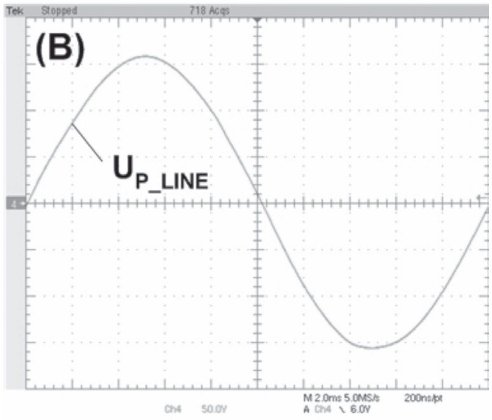


Fig. 25. Sinusoidal waves of the output voltage (U_{P_LINE}) produce by the Hybrid UPS for P_{LD} = 0kW (A) and for P_{LD} = 5kW (B).

CONCLUSIONS

Paper presents on-line hybrid UPS system. As static energy storage as applied supercapcitor. Second energy source is adjustable speed generating system supplying DC link voltage. A control concept of the UPS operation is developed according short and long failure of the supply utility voltage. The 5 kW H-UPS is designed, built and tested. The control unit is built using DSP processor is based on Shark from Analog Devices. The design and system stability tuning is achieved using PSIM software. Laboratory tests confirm high quality of the produced AC voltage during transients (voltage failure) and during steady state operation without external supply voltage.

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