Investigation of Supercapacitor Bidirectional Power Flow System

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Abstract - **It is possible to realize supercapacitor charging and discharging devices through BUCK-BOOST converter. In this paper alternative system of charging and discharging using supply side VS inverter for charging and supercapacitor side inverter for discharging of supercapacitor is investigate. In such device using H-bridge topology of Pulse Width regulated inverter a storage capacitors can be distributed in system as at input as also output and that allow to provide more efficient storage. Using in supercapacitor side a VS inverter allow to obtain reverse discharging of capacitor operating supply side inverter in quasi-BOOST regime. In the paper operational regimes of such device are described as also main expressions for calculation of processes are obtained. It's shown that most efficient operation and control case should be at boundary current shape of the primary winding of transformer. At some proper operational parameters it's possible to obtain maximum of transmitted power; for that also a voltage level of the secondary side supercapacitor have to be installed on proper level dependent on transformation ratio of transformer.**

Keywords – **Transistor, switch, capacitor, charging, frequency, voltage, current, duty, ratio, rectifier, windings**

I. INTRODUCTION

Supercapacitors are efficient electrical energy storage devices and are often applied in electrical drives for storage of extra power regenerated in braking processes of electrical motors. Usually for connection of supply source and supercapacitor BUCK-BOOST DC converters are applied [1,2,3]. However there are some disadvantages connected with relations between supply voltage and current and ones of supercapacitor. If voltage of supercapacitor is low such system would work with small duty ratio of BUCK converter not allowing obtain from supply large currents. Here is presented another version of converter on base of two voltage source inverters – one at supply side other – at supercapacitor side.

Scheme of the suggested device is presented in Fig.1. Here capacitors C1 and C2 are used as dividers of input supply DC voltage U_d and half of this voltage is periodically applied to the primary winding w1 of transformer. In the secondary circuit of transformer uncontrolled rectifier as part of VS transistor inverter is installed providing charging of capacitor. Switching of the primary circuit is provided by transistors T1, T2 with participating of clamp diodes V2 and V1 respectively.

II. OPERATION OF THE SCHEME IN DISCONTINUOUS CASE OF CHARGING CURRENT

Processes can be described as it is presented in Fig.2. Here at conducting of transistor T1 voltage of capacitor C1 is applied to the primary winding of transformer and its polarity is negative one , i.e. u_{T1}=-0.5U_d and voltage of the secondary winding provides rising of charging current i_2. When transistor is turned-off then current passing through the primary winding due to stored in transformer energy is passing through diode V2, i.e. voltage across the primary winding now is u_{T1}=0.5U_d.

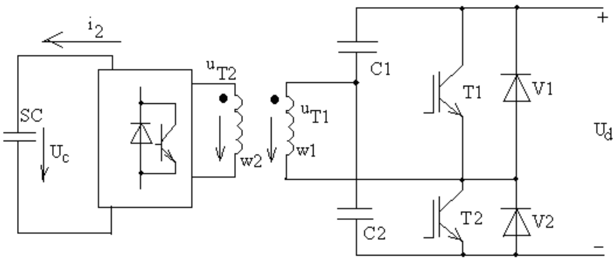

Fig.1. Scheme of charging device in charging case

Calculation of processes can be provided using equations in respect to current of the primary winding of transformer [4,5]

$$L_{Tr}\frac{di_1}{dt}=0.5U_d-nU_c \ , \tag{1}$$

$$L_{Tr}\frac{di_1}{dt}=0.5U_d+nU_c \ . \tag{2}$$

Equation (1) is applied for time interval DT_0 but (2) – for time interval t_2 when in the secondary winding polarity of voltage is changed and current i_1– descended to zero value. Here n is transformer ratio, i.e. relation of number of turns w1 to w2 but L_{Tr} is summary inductance of transformer reduced to the primary winding.

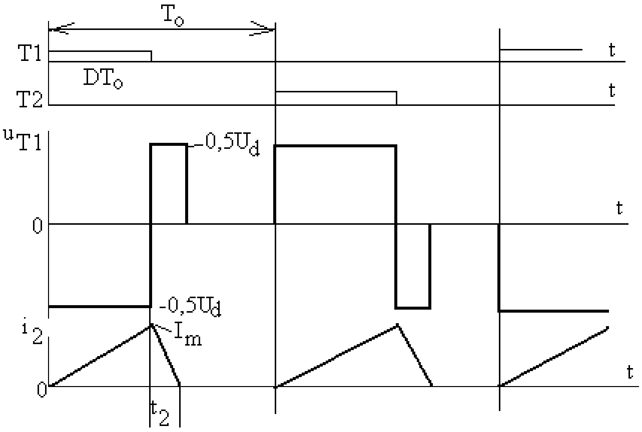

Fig.2. Diagrams of voltages and current for discontinuous operation case

For full deviations dimension di_2 can be substituted with magnitude of charging current I_m/n but dt in the first equation – with DT_0 , where D id duty ratio of conducting of transistor in process cycle T_0 which is half of switching cycle of transistors T_{sw}. In the second equation dt can be substituted with current descending time t_2 . Then from the both equations relation of current descending time t_2 to T_0 can be calculate using equation

$$\frac{t_2}{T_0}=\frac{D(0.5-nU_c^*)}{0.5+nU_c^*}\ . \tag{3}$$

If t_2 is equal to $(1-D)T_0$ then boundary operation case takes place when charging current of capacitor will be

$$I_{cb}=0.5I_m\ . \tag{4}$$

Such a boundary case will be at duty ratio

$$D_b=0.5+nU_c^*\ . \tag{5}$$

Here $U_c^*=Uc/U_d$ – a relative voltage of supercapacitor.

As it can be seen from (5) for obtaining a boundary operation case a relative voltage of capacitor must corresponds to condition $U_c^* <= \frac{0.5}{n}$.

In Fig.3 are presented diagrams of connection between n , U_c^* and D_b. At $D<D_b$ exist discontinuous operation case in respect to charging current.

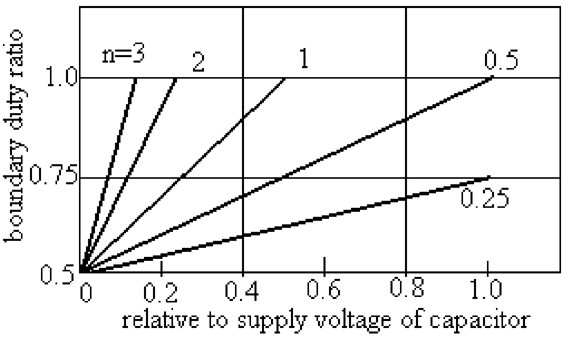

Fig.3. Dependence of the boundary duty ratio D_b on relative to the supply voltage one of supercapacitor at different ratio of transformer

At discontinuous operation case charging current of capacitor can be calculate as

$$I_{Cd}=0.5I_m(D+\frac{t_2}{T_0})=\frac{I_m D}{1+2nU_c^*}\ . \tag{6}$$

From eq. (1) magnitude of current i_2 can be calculate as

$$I_m=\frac{D(0.5-nU_c^*)nU_d}{L_{Tr}f_0}\ . \tag{7}$$

Applying (7) an averaged value of charging current is

$$I_{Cd}=\frac{D^2(0.5-nU_c^*)nU_d}{L_{Tr}f_0(1+2nU_c^*)}\ . \tag{8}$$

It can be seen that charging current is bigger if duty ratio too is bigger. If leak inductance and frequency is smaller than current also will be rising. Current is more also at smaller values of indicator nU_c^*. In Fig.4 is presented dependence curves of current I_{cd} on duty ratio and U_c^* at U_d=600 V, n=3, L_{Tr}=100μH and some values of f_0.

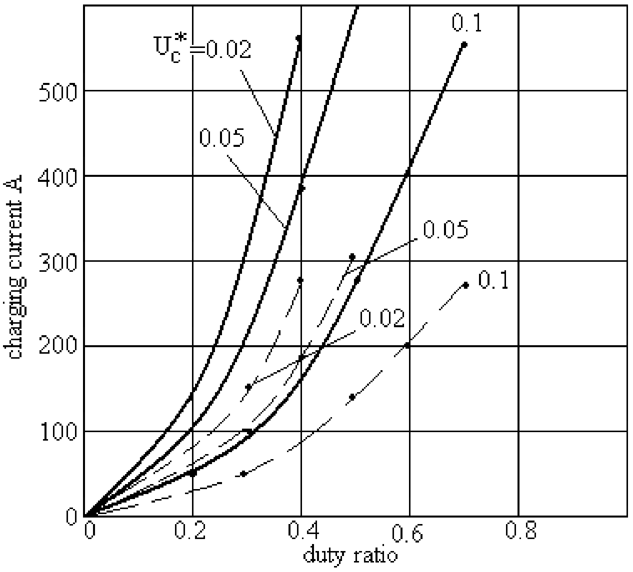

Fig.4. Dependence curves of charging current on duty ratio for U_d=600V, n=3, L_{Tr}=0.1mH at frequency f_0=2kHz (- - -) and 4 kHz and at relative voltage of capacitor 0.02, 0.05, 0.1

III. OPERATION IN BOUNDARY CHARGING CASE

In boundary operation case magnitude of charging current can be calculate as

$$I_{mb}=\frac{n}{L_{Tr}f_0}\left(\frac{U_d}{4}-\frac{U_c^2n^2}{U_d}\right) \tag{9}$$

and charging current respectively as

$$I_{cb}=\frac{n}{2L_{Tr}f_0}\left(\frac{U_d}{4}-n^2U_c^*U_c\right)\ . \tag{10}$$

Charging current at boundary operation case is biggest and it can be seen that for obtaining large enough charging current indicator $L_{Tr}f_0$ have to be small.

The maximal value of power transmitted at boundary case is $I_{cb}.U_c$ and at derivation this product by U_c it's possible to find that optimal value of capacitor voltage is

$$U_{co}=\frac{U_d}{2n}\sqrt{1/3}\ . \tag{11}$$

Applying this value an optimal power transmitted is

$$P_o=\frac{U_d^2}{24\sqrt{3}L_{Tr}f_0}\ . \tag{12}$$

Power and parameters of transformer should be calculate taking into account this P_0 and also duty parameter of charging device.

Choice of transformation ratio is connected with level of turn-off current of switches of supply side inverter. If n is smaller then I_{mb} is larger but turn-off current of switch is

$$I_{swm} = \frac{I_{mb}}{n} \ .$$

Therefore choice of the proper n is very essential. But if maximum power is transmitted then

$$I_{mb} = \frac{nU_d}{6L_{Tr} f_0}$$

and switch turn-off current does not depend on transformation ratio:

$$I_{swmb} = \frac{U_d}{6L_{Tr} f_0} \ .$$

Accepting different values of n and U_d=600 V it is possible calculate parameters U_{c0} , I_{mb} , I_{swm} , P_o . Indicator $L_{Tr}f_0$ are accepted as 0.2. At $L_{Tr}f_0$=0.2 at all range of transformation ratio power P_o=43.35 kW but I_{swm}=500 A. Reducing transformation ratio a voltage of capacitor have to be increased but charging current decreases (Fig.5). If indicator $L_{Tr}f_0$ is increasing then as power transmitted as also charging current both are decreasing.

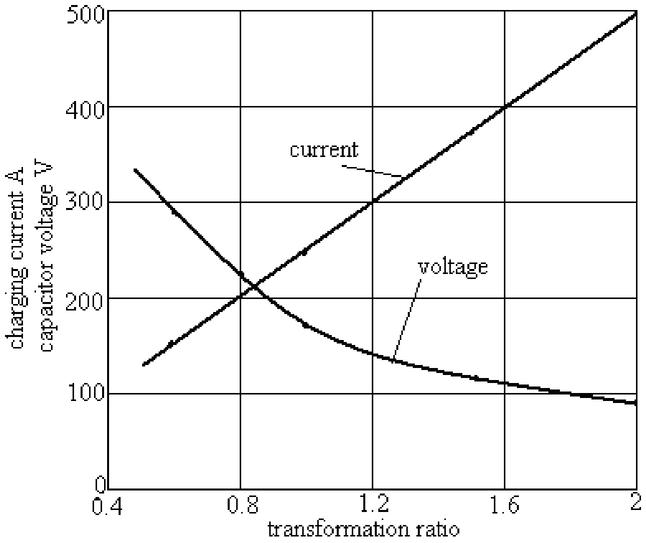

Fig.5. Dependence of capacitor voltage and charging current on transformation ratio at maximum of transmitted power

In Fig.6 are presented simulated by PSIM package diagrams of charging current and supply inverter half-leg circuit of capacitor C1. Diagrams are obtained at U_d=600 V, n=1.5, $L_{Tr}f_0$=0.2 , voltage U_{c0}=115.6 V and duty ratio D_b=0.789 (switching frequency is 1 kHz). As it can be seen magnitude of charging current as also switch turn-off current both are correctly according to the calculated values and power transmitted is 43.35 kW.

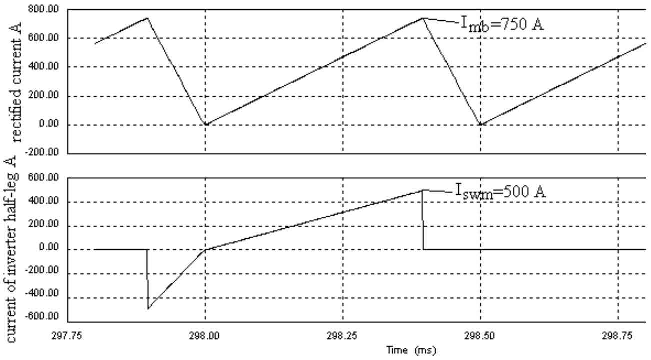

Fig.6. Simulated diagrams of currents in charging and supply capacitor circuits at U_d=600 V, n=1..5 , U_{c0}=115.6 V , L_{Tr}=0.1mH, f_0=2 kHz

Current in the primary winding of transformer can be presented as of triangular shape and then RMS value of this current can be presented as $I_{swm}/\sqrt{3}$ and calculation power of transformer at transmitting of maximum power will be

$$S_{Tr} = \frac{I_{mb}.U_d}{n.2\sqrt{3}} = \frac{U_d^2}{12\sqrt{3}L_{Tr} f_0} = 2P_0 \ . \tag{13}$$

Because regeneration process at braking of motor has intermittent character it's possible apply raised values of current density of windings up to j=(4-6).10^6 A/m^2 and sometime even more that allow decrease size of transformer and its leak inductance too.

Calculations done show that leak inductance is smaller if frequency is higher. It is connected with possibility to decrease as number of turns as also size of transformer. For instance if frequency is raised 5 time from f_0=2 kHz up to 10 kHz then leak inductance of transformer should be decreased 8 time. As result indicator $L_{Tr}f_0$ should be decreased 1.6 time but anyway it is quiet difficult to obtain sufficient small meanings of the indicator that in its order don't allow obtain large values of transmitted power.

It's also bad that calculation power of transformer is twice higher as transmitted active power and it means that power factor of transformer is 0.5.

IV. OPERATION OF SCHEME AT SUPERCAPACITOR DISCHARGING

For realization of supercapacitor discharging have to be activate both inverters of the scheme but supply inverter would works as BOOST converter when transistors T1 and T2 alternately are shortening circuit of primary winding of transformer in series with one or another supply divider capacitor. Operation scheme and diagrams of switch operation are presented on Fig.7.

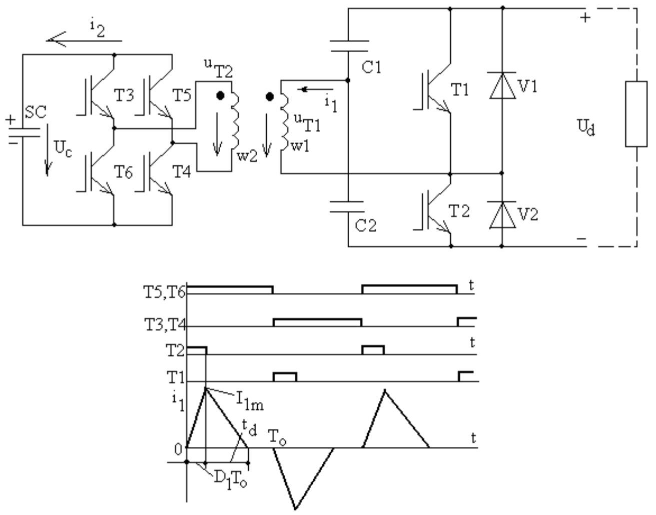

Fig.7. Operation scheme for discharging of supercapacitor

When switch T2 together with ones T5,T6 are turned-on then current of primary winding i_1 starts to rise in contour w_1-T2-C2-w_1 by influence of series connected voltage of winding w_1 and voltage of capacitor C2:

$$L_{Tr}\frac{di_1}{dt} = nU_c + 0.5U_d \tag{14}$$

but after turn-off of transistor T2 current i_i closes up through diode V1 and capacitor C1 charging the later. Eq. will be as follows

$$L_{Tr}\frac{di_1}{dt} = nU_c - 0.5U_d \ . \tag{15}$$

From the (1) accepting linear in time rise an amplitude of i_1

$$I_{1m} = \frac{D_1(nU_c + 0.5U_d)}{L_{Tr} f_o} \tag{16}$$

where D_1 is duty ratio for switches T1,T2 in process cycle T_o. Accepting application of supercapacitor voltage U_{co} (11), i.e. assuming operation at maximum of reversed to supply power, this amplitude for boundary case of current i_1 can be calculate as

$$I_{1m} = \frac{U_d}{6L_{Tr} f_0} \ . \tag{17}$$

Decreasing of current i_1 to zero value longs a time interval

$$t_d = \frac{L_{Tr} I_{1m}}{0.5U_d - nU_c}$$

or applying (11) and (17) at accepted for maximum reversed power the boundary case

$$t_d = \frac{1}{f_0(3-\sqrt{3})} = (1 - D_{1b})T_0 \ . \tag{18}$$

Duty ratio for this boundary case is

$$D_{1b} = 0.5 - \frac{1}{2\sqrt{3}} \ . \tag{19}$$

Taking into account equations obtained the maximum power reversed to supply at boundary case with optimal supercapacitor voltage can be find as

$$P_{revm} = \frac{I_{1m}U_d}{4\sqrt{3}} = \frac{U_d^2}{24\sqrt{3}L_{Tr} f_0} \ . \tag{20}$$

The apparent power of transformer again is twice so large as power reversed to supply:

$$S_{Tr} = \frac{I_{1m}}{\sqrt{3}} 0.5U_d = \frac{U_d^2}{12\sqrt{3}L_{Tr} f_0} \ . \tag{21}$$

In Fig.8 are presented diagrams of currents at reverse operation of system at discharging of supercapacitor.

As it can be seen averaged current of supercapacitor is 375 A but averaged current transmitted to supply circuit – 70 A, i.e. system is working with maximum of reversed to supply circuit power close to 42 kW.

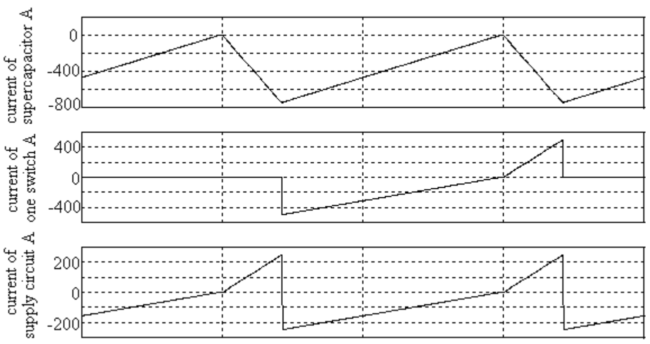

Fig.8. Diagrams of supercapacitor current, current of one switch in primary side of transformer and current in circuit of DC source at voltage of supercapacitor U_{c0} , transformation ratio n=1.5 , $L_{Tr}f_o$=0.2 , U_d=600 V, D_{1b}=0.211

V. OPERATION OF SYSTEM AT INTERMITTENT POWER FLOW

For evaluation of system's operability have been provided PSIM simulation of processes at intermittent power flow. Diagrams describing the process are presented in Fig. 9. Here at first stage to supply source load with 22.8 kW was applied and as result system is operating at transmitting power from supercapacitor to supply source circuit. Because duty ratio of source side switches in process cycle is 0.211 the system is working with maximum reversed power 42 kW and as its result voltage of supercapacitor with capacity 200 F is gradually decreasing in loading interval of 0.33 s on 0.6 V. In this process power transmitted is bigger as load's one and as result voltage of supply side capacitors (each with capacity 1 F) is rising-up for 20 V to 620 V.

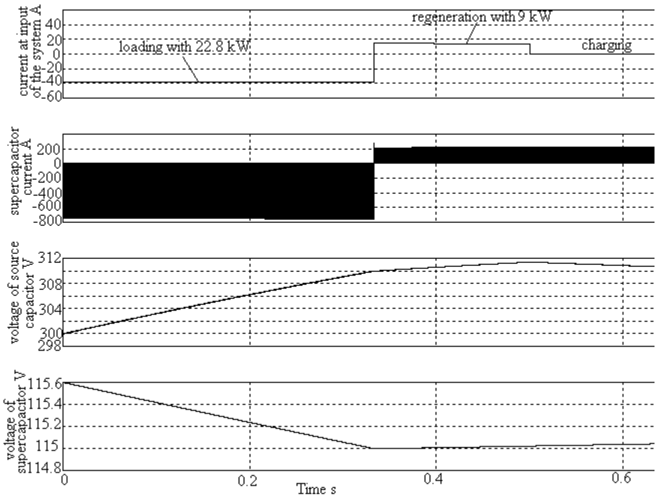

Fig.9. Diagrams of currents at input of the converter and in circuit of supercapacitor (positive values respectively loading of device and charging), as also voltage of one capacitor of supply side divider and of supercapacitor at loading with power 22.8 kW, regeneration on the device with 9 kW and normally charging of supercapacitor at duty ratio D_{1b}=0.211 in the process cycle

In the loading part energy supplied from supercapacitor 13.84 kJ goes to the load (7.74 kJ) and to rising of voltage of supply side capacitor divider (6.1 kJ).

When load is turned-off but starts regeneration then operation of supercapacitor side inverter is stopped but in the case duty ratio for supply side inverter switches was not changed and as result current of supercapacitor charging is smaller as it would be available with operating at D_b. Therefore supercapacitor can't absorb all energy transmitted to the device and as result voltage of supply side capacitors in duration of power regeneration is slightly rising too. After end of regeneration process in the case starts a normally charging of supercapacitor and again through unchanged duty ratio - with relatively small current (Fig.9).

For better operation of energy storage device it's possible introduce in system of control feedback on value of duty ratio by supply side capacitor voltage: if the voltage is rising in loading regime then duty ratio for switches of supply side inverter have to be decreased and vice versa but in regeneration case – if voltage is rising then this duty ratio have to be raised too. Control system also must check voltage change range of supercapacitor especially on maximal admissible level.

Energy stored in the input and output capacitors depend on admissible maximum values of its voltages. If for instance the total capacitance of the both input capacitors is 0.5 F and admissible value of voltage is 650 V at rated for system 600 V then stored in the input capacitors extra energy can reach 15.6 kJ. Almost same stored extra energy can be reached at admissible voltage of output capacitor 120 V at rated 115 V with capacity 25 F. In total extra energy stored at the parameters can reach little above 30 kJ but taking into account the maximum available transmitted through transformer power (as it was shown at $L_{Tr}f_0$=0.2 and U_d=600 V it was about 42 kW) charging process can longs 0.71 s.

In common case volume of capacitors can be obtained at some accepted as most heavy input charging current which usually has triangular shape with front edge magnitude I_{mch} and time length t_{ch}. From circuit of input capacitors C1, C2 through transformer to SC is transmitted current P_0/U_{c0} and current of the input capacitors is ($I_{mch}>P_0/U_{c0}$)

$$i_{C1}=I_{mch}\left(1-\frac{t}{t_{ch}}\right)-\frac{P_0}{U_{c0}} \qquad (22)$$

but common voltage of input capacitors is

$$u_{c12}=\frac{I_{mch}.t}{C_{12}}\left(1-\frac{t}{2t_{ch}}\right)-\frac{P_0.t}{U_{c0}C_{12}}+U_{c120} \qquad (23)$$

where C_{12} is total capacitance of the both serial connected input capacitors, U_{c120} – initial voltage (usually rated one).

Maximum of voltage will be at time instant t_m

$$t_m=t_{ch}\left(1-\frac{P_0}{U_{c0}I_{mch}}\right)<=t_{ch}\ . \qquad (24)$$

Then overvoltage across input capacitors reach

$$\Delta U_{c12m}=\frac{I_{mch}.t_m}{C_{12}}\left(1-\frac{t_m}{2t_{ch}}\right)-\frac{P_0.t_m}{C_{12}U_{c0}}\ . \qquad (25)$$

Taking into account admissible maximum value of U_{c12m} from this expression can be obtained proper value of C_{12} but each capacitor must have twice bigger volume.

If for instance to device with maximum power transmitted P_0=42 kW and U_{c0}=115 V charging current pulse with I_{mch}=450 A and t_{ch}=5 s at C_{12}=0.5 F is applied then $\Delta U_{c12m}=79.86$ V but admissible value is only 50 V up to 650 V. It means that volume of C_{12} have to be increased up to 0.8 -1 F.

Output supercapacitor is charged with current P_0/U_{c0} and its voltage will rise up by $\Delta U_{sc}=\dfrac{P_0.t_{ch}}{U_{c0}.C_{sc}}$ and at calculation pattern if ΔU_{sc}=10 V then it's necessary install capacitance about 200 F.

VI. CONCLUSIONS

1. System with inverters at primary and secondary part of transformer can provide bidirectional power flow about of equal volume in each direction.
2. Input side capacitors have to be with smaller capacity and larger voltage as one installed at the secondary side of transformer. For obtaining maximum transmitted power the secondary side capacitor have to be installed with proper voltage dependent on transformation ratio but duty ratio of primary side switches must be set on proper value, bigger one for charging output supercapacitor.
3. Most efficient operation regime of primary side inverter is for providing the boundary case current in primary winding of transformer.
4. Calculation power of transformer have to be twice bigger as transmitted from or to output supercapacitor power.

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Ivars Raņķis, Jānis Zaķis. Superkondensatora uzlādes sistēmas izpēte

Parasti superkondensatoru izlāde-uzlāde tiek veikta attiecīgi caur spriegumu paaugstinošo un pazeminošo kondensatoru. Šādas sistēmas galvenais trūkums ir ieslēgts sakarībās starp ieejas strāvu un nepieciešamo impulsregulatora relatīvo ieslēguma laiku pie pazemināta uzkrājēja superkondensatora sprieguma, kas liek darboties ar ieejas strāvu mazāku par slodzes. Pielietojot transformatoru ar invertoriem ieejas pusē un izejas pusē, kas saistīta ar superkondensatoru, ir iespējams panākt pietiekami efektīvu un labi saskaņotu jaudas pārvadi no ieejas ķēdes uz superkondensatora. Pie tam, veidojot ieejas invertoru pēc pustilta shēmas, ir iespējams uzstādīt arī ieejā mazas kapacitātes supekondensatorus kā sprieguma dalītājus, kas ļauj izkliedēt lādēšanas enerģiju pa dažādām ķēdēm., tā panākot iespēju neuzstādīt ļoti lielas kapacitātes galveno superkondensatoru. Darbā aplūkoti šādas sistēmas darbības režīmi, aprakstīti elektromagnētiskie procesi, dotas galvenās izteiksmes, kas ļauj noteikt sistēmas parametrus. Parādīts, ka efektīgākais darbības režīms ir ar transformatora primārās puses invertora nodrošinātu primārā tinuma strāvas robežgadījumu, pie tam procesu regulēšana gan galvenā superkondensatora uzlādes, gan izlādes režīmā tiek nodrošināta ar transformatora primārās puses invertora slēdžu relatīvā ieslēguma ilguma regulēšanu. Atrasti noteikumi, kas nosaka maksimālo jaudas pārvadi abos virzienos, un tie saistīti gan ar ieejas invertora slēdžu ieslēguma relatīvo laiku, gan ar uzstādāmo superkondensatora sprieguma līmeni un transformācijas koeficientu. Aplūkota sistēmas darbība secīgas jaudas pārvade vienā un pēc tam otrā virzienā. Doti norādījumi gan ieejas, gan izejas superkondensatoru kapacitātes izvēlei.

Иварс Ранькис, Янис Закис. Исследование системы заряда суперконденсатора

Обычно заряд-разряд суперконденсатора проводится через импульсный регулятор, понижающий-повышающий напряжение. Главный недостаток такой системы заключается в том, что между напряжениями конденсатора и заряжающей сети существует отношение, которое определяет, что ток, поступающий из сети, меньше тока в цепи суперконденсатора, чем ослабляется эффект использования энергии рекуперации на зарядное устройство. Используя трансформатор с инверторами напряжения на каждой стороне трансформатора, появляется возможность обеспечить согласованную передачу энергии с входной цепи к суперконденсатору. При этом используя полумостовую схему входного инвертора, появляется возможность использовать как делители входного напряжения суперконденсаторы небольшой емкости, что позволяет распределить накапливаемую энергию по различным цепям, что в свою очередь позволяет уменьшить необходимую емкость главного суперконденсатора на вторичной стороне трансформатора. В работе рассматриваются режимы работы такой системы, описываются электромагнитные процессы, даются главные выражения, позволяющие определить параметры элементов системы. Показано, что наиболее эффективным режимом работы системы является такой, при котором из-за действия ключей инвертора на первичной стороне трансформатора, удается получить гранично-прерывистый ток первичной обмотки трансфопматора. При этом регулирование процессов как при заряде, так и при разряде главного конденсатора осуществляется одними и теми же ключами инвертора на первичной стороне трансформатора. Найдены условия, при которых возможно получить максимальную передаваемую мощность через трансформатор и эти условия включают в себе как необходимые относительные длительности включения ключей входного инвертора, так и выбор оптимального уровня напряжения главного суперконденсатора и коэффициента трансформации. Рассмотрена работа системы при поочередном изменении направления потока энергии; даны указания по выбору параметров как входных, так и выходных суперконденсаторов.