Project code STCU/5388. Development, realisation and testing of the sample of high-speed phase shift transformer with thyristor control. Period of realisation 2011-2012. Project Manager, D.Sc.. BerzanVladimir.

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Project team

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Purpose and Objective

One of the most important technical parameters of any electrical installation is its settlement (or typical) capacity which characterizes weight, the sizes and, finally, product cost, and also the expenses connected with its transportation and installation on transformer substation.

Intended for work in high-voltage networks phase shift devices are traditionally made on the basis of two-transformer execution (two-core design). Thus one of transformers carries out functions of a regulating (exciting) element, and the second - functions of phase shift (additional) element. It means, that settlement capacity of such unit will be practically twice more capacities of loading on which it should be calculated at a preset value of the maximum phase shift. In turn, settlement capacity of PST is in direct dependence on the maximum value of phase shift on conditions of its work on transformer substation, i.e. the more the maximum value of phase shift, the more total settlement capacity of the elements forming the device. The specified circumstance is the main deterrent by consideration of questions of PST practical application in electric networks. The purpose of the offered project consists in increase of technical and economic competitiveness of PST in comparison with other control facilities modes of electric systems and expansion of area of its application.

As the preliminary analysis, total settlement capacity of the elements forming the device shows, can be considerably reduced due to partial transfer of the exciting transformer in an autotransformer mode. As much as possible achievable effect takes place provided that half of capacity through passage is transferred autotransformer by, and half - purely transformer way. Thus settlement capacity of an exciting element remains same, as well as for a traditional circuit variant, and settlement capacity of an additional element decreases

practically twice. Thus, the resulting effect of decrease in settlement capacity of all unit makes 25 %. Double weight reduction and dimensions of the additional transformer will favor to placing of both elements in one general transformer tank that it is necessary to consider as the most preferable constructive solution. Besides, partial use of autotransformer effect will promote decrease of short circuit resulting resistance of installation, and also power losses in transformer windings. Offered to realization within the limits of the competitive project circuit variant of PST contains basic novelty and requires physical modeling.

One more deterrent factor at the solution of questions concerning practical application of PST is high enough cost of power semi-conductor elements that compels to limit functional properties of control facilities to ability of realisation of minimum necessary operations to the detriment of potentially existing possibilities. The economy of means received for the account of decrease of typical capacity of PST, can be used for expansion of its operating functions at the expense of more free application of power electronic switchboards. In particular, it allows to lower the general number of modules in variant of PST with pulse-width modulation (PWM), considered in article of employees McGill University specified above where each module represents one step of regulation of phase shift. In the offered competitive project each module can represent two and more steps of regulation.

Expected Results

In the frame of the project will be executed fundamental and experimental researches which will allow expanding further the theory and practice of creation and use of the high-speed phase-shift devices for management of modes of electropower systems.

The laboratory sample of the high-speed phase-shift transformer by capacity near10 kVA with regulated (in a range from $\psi = 0°$ to $\psi = 60°$) phase shift angle will be really developed, made and tested. The specified range will be divided into 14 steps due to using of two modules of the additional transformer element, one of which is intended for performance of functions of the rough regulation, the second - functions of exact regulation (at total typical capacity of these modules twice it is less, than typical capacity of a corresponding exciting element). At the expense of so significant amount of discrete steps of switching in some cases it is possible to refuse completely use of principles of pulse-width modulation and the necessity of application of harmonious filters connected with it.

By results of the performed work principles of the device construction intended for a direct power exchange between systems with various standards on accuracy of maintenance of frequency of an alternating current, conditionally called by executors «ALTERNATIVE CURRENT LINK» will be formulated.

It is necessary to consider as additional result of the performed work the scientific publications connected with given subjects and patents.

Scope of Activities

Fundamental and the experimental researches making the scope of the offered project, and also works necessary for performance, organizational - technical actions, can be formulated as follows:

- The analysis and comparison of various circuit variants of phase shift transformer (PST) concerning possibility and expediency of their compatibility with elements of power electronics means

- A choice of the most perspective circuit variant of PST for experimental realization in laboratory conditions, working out of principles of realization of step switching

- Working out of a mathematical apparatus for the description of physical processes in the elements forming PST, at symmetric regulation of phase shift between output and input voltages of device

- Electromagnetic calculation of the laboratory sample elements by capacity 10 kVA on the voltage 220 V, providing step (14 steps) regulation of phase shift of output voltage in a range from $\psi = 0°$ to $\psi = 60°$

- Development of the technical project on designing and device manufacturing

- Working out of constructive elements of the laboratory sample, preparation of equipment and material base for its manufacturing

- Manufacturing of the laboratory sample by forces of project team

- Experimental check of the device on conformity of real parameters to those parameters which are specified in the technical project

- Check of working capacity of the device in various modes by means of use of mechanical switches as substitutes of power electronic keys

- Working out of the basic scheme of power electronics, calculation and a choice of the basic elements providing performance of switching operations

- Preparation of element base and installation of a power part of a control system

- Check of work of the device in the conditions of application of power electronic control means and comparison of last results with earlier received data at use of mechanical switches

- Development of automated management, protection and control system of the device state, providing realization of potential possibilities of high-speed PST

- Manufacturing, installation and test of the control system

- Development of the experimental researches program of the laboratory sample on conformity to the declared characteristics

- Preparation and acquisition of the necessary instrumentation for carrying out of high-grade experimental researches and tests

- Finishing tests of the device under the full program, processing and the analysis of the received results, registration of the report by results of the performed work

- Preparation and representation of the generalizing scientific and technical report on the executed work, containing offer on its further development.

Preliminary results

First quarter report

The main objective of the first stage in the carried out research work is the choice of effective basic connection of transformers elements (forming the PST) that will allow us to reduce the sizes, weight and the cost of the equipment in general. In this regard, we have developed the several new variants of the circuit configuration for two-cores PST which we think might be promising for practical application. At this stage of the work as a control principle of PST we consider the use of OLTC (On Load Tap Changer) bearing in mind that in the future we will use of Power Electronics. The results achieved for each variant are estimated by comparison with a well-known technical solution that is called as Marcerau Connection. For each variant it was developed the corresponding mathematical model (by use of MATLAB/ Simulink procedures). Each model designed for the same throuput power capacity and the same maximum value of the phase shift between input and output voltages of PST ($\psi_{\max} = 60^\circ$). As a comparison criterion, the following key indicators are adopted:

ΔP_{id} - Power losses of PST in idling mode experiment,

ΔP_{sc} - Power losses of PST in short circuit mode experiment,

ΔP_{Σ} - Total power losses of PST as result of two tests $\left(\Delta P_{\Sigma} = \Delta P_{id} + \Delta P_{sc} \right)$,

S_{PST} - Rated capacity of PST in load experiment $\left(S_{PST} = S_p + S_q \right)$,

S_p - Rated capacity of boosting unit,

S_q - Rated capacity of exiting unit.

The testing results of idling and short circuit modes allow us to provide the equivalent circuit of PST (Fig.1) which can be used to determine the relationship between input and output regime indicators of PST in condition of the load current changing or the angle ψ

$$U_1 = U_s \quad r_{id} \quad x_{id} \qquad x_{sc} \qquad r_{sc} \qquad U_2 \qquad \dot{K} = e^{j\psi} \qquad U_r = U_2 e^{j\psi}$$

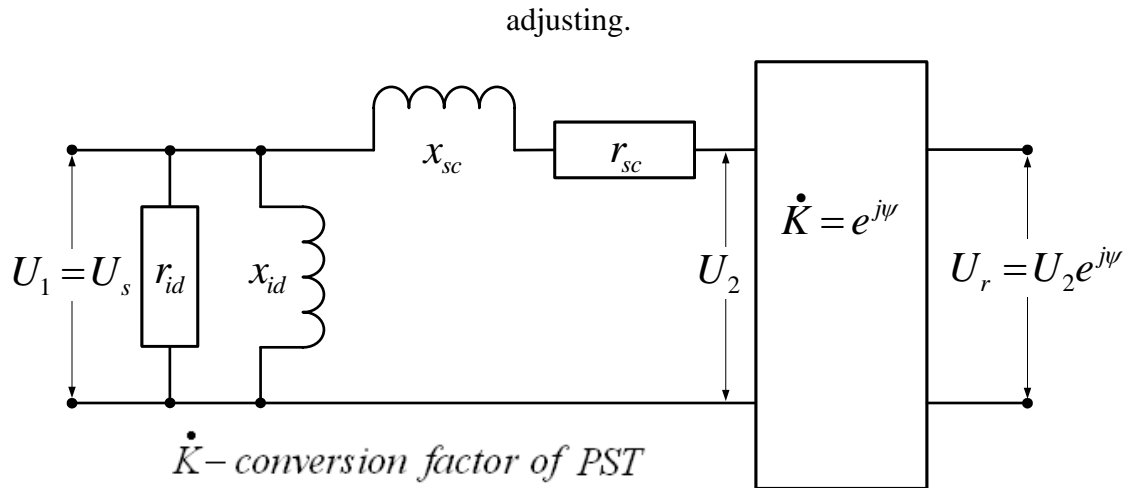$\dot{K}$ – *conversion factor of PST*

Fig.1. Equivalent circuit of PST

The testing results of load modes for variants presented give us the possibility to determine the rated capacity of each element that is the part of PST as well as identify the ways to improve the effectiveness of power equipment. The reduction in weight and dimension of elements forming the two-cores PST will foster the placement of exiting and boosting transformers in common tor both of them transformer tank , will provide more favorable conditions for transport and accommodation of phase shifting transformer to the transformers substations. In addition the decrease in the rated capacity of boosting transformer S_p is means a corresponding reduction in the rated capacity of Power Electronics that form a very significant (if not major) part of the full cost of the device.

1. Traditional schematic diagram of PST

Schematic diagram of PST based on dual-cores Marcerau Connection technology is presented in Fig.2. Elements (components) related to the exiting transformer are labeled by indexes "q" and elements related to the boosting transformer are labeled by indexes "p".

Fig.2. Traditional variant of PST (Marcerau Connection)

Input electric values are labeled by indexes "s" and output electric values are labeled by indexes "r":

U_s, I_s - Voltage and current at the input end of PST,

U_r, I_r - Voltage and current at the output end of PST,

ψ - Phase difference between output voltage U_r and input voltage U_s (or between I_r and I_s),

$\left.\begin{matrix} U_r \\ I_r \end{matrix}\right\} = e^{j\psi} \cdot \left\{\begin{matrix} U_s \\ I_s \end{matrix}\right.$ - Relationship between input and output values of PST for the idling mode of operation.

The summarized results for the idle mode testing of device are presented in Table.1. The tests were performed at the different values of voltage kU_{2q} that comes from winding W_{2q} by the use of OLTC (On Load Tap Changer) regulating contacts and applied to the winding W_{2p}. The line "Position" in this table defines the virtual position of OLTC contacts (total of 9 positions) which provide the appropriate values of angle ψ. These positions of OLTC will be used for all subsequent versions of PST. All principal values of the measured and calculated capacities are related to the one phase of three-phase device.

Table 1

Position	1	2	3	4	5	6	7	8	9
$kU_{2q}(V)$	0	27.5	55	82.5	110	137.5	165	192.5	220
$U_{sr}(V)$	0.365	33.1	65.7	97.3	127.5	156	182.5	207	229.4
ψ°	0.09	8.3	16.5	24.4	32.3	39.7	46.9	53.8	60.1
$I_{id}(A)$	.308	.314	.332	.361	.4	.446	.496	.551	.606
$\Delta P_{id}(W)$	27.4	27.8	29.1	31.1	33.7	36.9	40.4	44.1	47.9
$\Delta Q_{id}(VAr)$	65.3	66.6	70.7	77.1	85.5	95.6	106.8	118.7	131.0
$U_{1q}(V)$	397.9	396.8	393.7	388.7	382.0	373.9	364.7	354.6	343.9
$Z_{id}(Ohm)$	746.7	732.5	692.8	637.1	575.0	515.7	463.7	417.4	379.5
$r_{id}(Ohm)$	1930	1903	1818	1701	1570	1433	1309	1199	1104
$x_{id}(Ohm)$	808.9	794.3	749.6	687.0	617.9	553.1	496.2	444.8	403.5

✳-voltage U_{1q} determines the change in magnetic induction in the cores of exiting transformer under control of angle ψ.

Measured values are: $U_{sr}, \psi^\circ, I_{id}, \Delta P_{id}, \Delta Q_{id}, U_{1q}$.

Calculated values are: Z_{id}, x_{id}, r_{id}.

The summarized results for the short-circuit mode testing of device are presented in Table2.When testing, the value of the short circuit current of device was fixed at the level I_{sc}=12A=const.

Table2

Position	1	2	3	4	5	6	7	8	9
$U_{sc}(V)$	29.3	29.5	29.9	30.6	31.5	32.6	33.8	35.1	36.4
$\Delta P_{sc}(W)$	108.0	108.5	108.8	109.8	110.8	112.3	113.7	115.3	116.7
$\Delta Q_{sc}(VAr)$	334.3	337.3	342	350.8	361.8	375.7	390.5	406.7	422.5
$Z_{sc}(Ohm)$	2.44	2.46	2.49	2.55	2.63	2.72	2.82	2.93	3.03
$r_{sc}(Ohm)$	.75	.753	.756	.763	.769	.78	.789	.801	.81
$x_{sc}(Ohm)$	2.322	2.342	2.372	2.433	2.515	2.606	2.707	2.818	2.919

Measured values are: $U_{sc}, \Delta P_{sc}, \Delta Q_{sc}$

Calculated values are: Z_{sc}, r_{sc}, x_{sc}.

The characteristics of active (r_{id}) and reactive (x_{id}) components of impedance (Z_{id}) for the idle mode of PST as well as characteristics of active (r_{sc}) and reactive (x_{sc}) components of impedance (Z_{sc}) for the short circuit mode of PST are presented in Fig.3 and Fig.4, respectively.
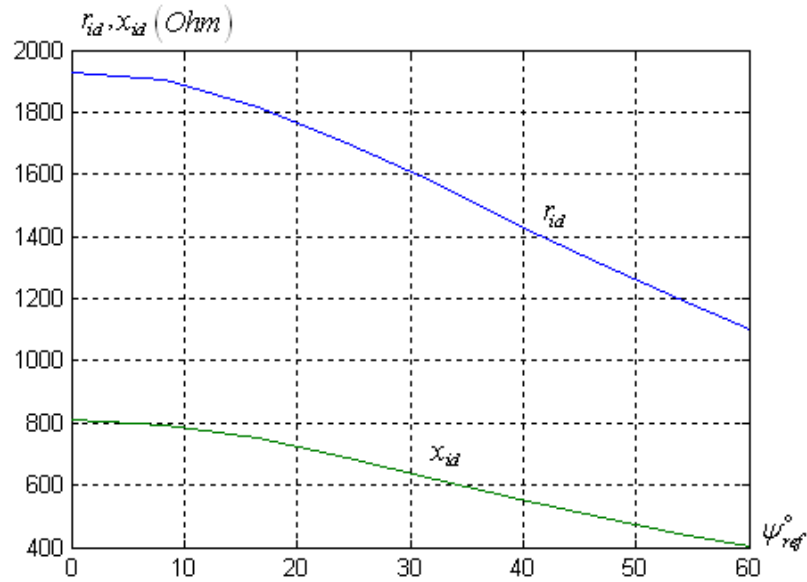

Fig.3. Characteristics of active (r_{id}) and reactive (x_{id}) components of impedance (Z_{id}) for the idle mode of PST
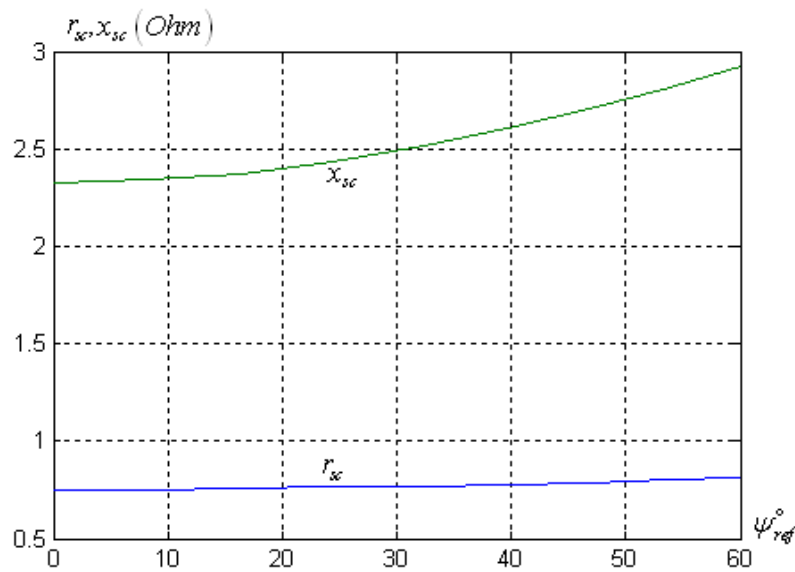

Fig.4.Characteristics of active (r_{sc}) and reactive (x_{sc}) components of impedance (Z_{sc}) for the short circuit mode of PST.

The nature of change in active power losses of PST is presented in Fig.5, where $\Delta P_{\Sigma} = \Delta P_{id} + \Delta P_{sc}$. Further, these characteristics will be compared with the analogical characteristics of other PST variants for an objective evaluation of the effectiveness of proposed variants.
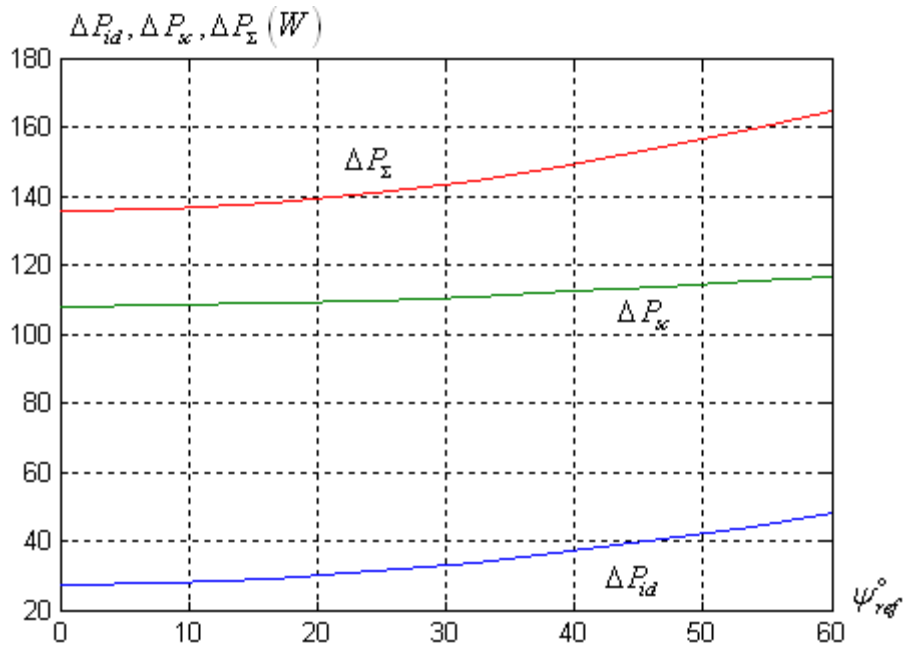
Fig.5. Nature of the change of power losses versus the angle
ψ in the PST of Marcerau Connection.

The argument ψ_{ref} with respect to which the characteristics on Figures 3,4 and 5 are presented, correspond to the idling mode phase shift $\psi°$, then there is $\psi_{ref} = \psi°$ from Table 1.

As a result of load tests one can determine the rated capacity for all elements forming the PST. For the generality of the further results, the rated capacities of PST, as well as separate individual elements, are presented through the full load power at the output terminals of device which can be expressed as $S_r = U_r I_r$. (S_r -value is installed at the design stage of RST).

The short circuit experiment (Table 2) was made at the condition $I_{sc} = 12A$. Accordingly, during load tests we provide $I_r = 12A =$ **const** by attaching to the output terminals of PST the appropriate active load resistance.

The load mode testing results for Marcerau Connection samples are presented in Table 3. Along with indicators characterizing the load mode (L), in this table are presented also some of indicators characterizing the idling mode (I) of PST that could be used in future reckonings.

The PST in question provides the ability of symmetrical control the phase angle range within $\pm 60°$. With increasing of angle ψ in the positive direction, it is respectively increases the power through PST, and vice versa, power trough PST is reduced with increasing the angle ψ in the negative direction. Therefore, position $\psi = +60°$ should be considered as the severest for equipment and corresponding conditions must be taken as a settlement for design of PST.

In accordance with standard definition, the rated capacity of any transformer can be presented as a half sum of rated capacities of all its windings. In turn, the rated capacity of each winding is a product of the maximum current at maximum voltage of this winding which selected from all possible modes of transformer operation. Voltages and currents in Table 3 marked with yellow marker, are the basic for calculation of rated capacity for corresponding winding.

In accordance with foregoing, we find the values of the rated capacities for the individual elements of PST.

Rated capacity (S_p) of boosting transformer $S_p = \dfrac{S_{W_{1p}} + S_{W'_{2p}} + S_{W''_{2p}}}{2} = 2799$ W,

Rated capacities $\left(S_{W_{1p}}, S_{W'_{2p}}, S_{W''_{2p}} \right)$ for individual windings of this transformer have the following meanings:

$S_{W'_{2p}} = 115 \cdot 12.25 = 1408 W$

$S_{W_{1p}} = 229.6 \cdot 12.2 = 2801 W$

$S_{W''_{2p}} = 114.8 \cdot 12.1 = 1389 W$

Rated capacity (S_q) of exiting transformer $S_q = \dfrac{S_{W_{1q}} + S_{W_{2q}}}{2} = 2852 W$

Table 3

Position		1 U(V)	1 I(A)	2 U(V)	2 I(A)	3 U(V)	3 I(A)	4 U(V)	4 I(A)	5 U(V)	5 I(A)	6 U(V)	6 I(A)	7 U(V)	7 I(A)	8 U(V)	8 I(A)	9 U(V)	9 I(A)
ψ°_{ref}	I	.09		8.3		16.5		24.4		32.3		39.7		46.9		53.8		60.1	
ψ°	L	-6.1		2.1		10.2		17.9		25.5		32.7		39.5		46		52.1	
$U_{sr}(V)$	I	.342		33.1		65.8		97.4		127.6		156.1		182.7		207.3		229.7	
$U_{sr}(V)$	L	26.0		12.6		40.9		71.0		99.9		127.1		152.5		175.9		197.3	
$U_r(V)$	L	220.3		220.3		220.2		220.0		219.8		219.5		219.2		218.8		218.4	
$\Delta P(W)$	L	124.3		124.9		126.5		129.1		132.5		136.5		140.8		145.5		150.2	
Parameters		U(V)	I(A)	U(V)	I(A)	U(V)	I(A)	U(V)	I(A)	U(V)	I(A)	U(V)	I(A)	U(V)	I(A)	U(V)	I(A)	U(V)	I(A)
W_{1p}	I	.137		33.2		65.8		97.4		127.6		156.1		182.7		207.2		229.6	
W_{1p}	L	1.4	12.2	32.4	12.2	63.9	12.1	94.1	12	122.7	11.8	149.5	11.6	174.2	11.3	197	11	217.7	10.7
W'_{2p}	I	.295		16.6		32.9		48.7		63.8		78.1		91.4		103.7		115	
W'_{2p}	L	13.1	12.25	7.1	12.25	21.3	12.25	36.6	12.25	51.2	12.25	65.1	12.25	78	12.25	89.9	12.25	100.8	12.25
W''_{2p}	I	.07		16.6		32.9		48.7		63.8		78		91.3		103.5		114.8	
W''_{2p}	L	13.0	12.1	5.5	12.1	19.7	12.1	34.6	12.1	48.8	12.1	62.2	12.1	74.7	12.0	86.2	12.0	96.7	12.0
W_{1q}	I	397.9		396.8		393.7		388.7		382.0		373.9		364.7		354.6		343.9	
W_{1q}	L	389.2	.2	388.5	1.2	385.7	2.2	381.1	3.2	374.9	4.1	367.5	5.0	359.0	5.8	349.8	6.6	340.1	7.3
W_{2q}	I	.136		33.2		65.8		97.4		127.6		156.1		182.7		207.2		229.6	
W_{2q}	L	1.35	12.2	32.4	12.2	63.9	12.1	94.1	12	122.7	11.8	149.5	11.6	174.2	11.3	197.0	11.0	217.7	10.7

I – idle condition, L –load conditions, $I_r = 12A$, $U_s = 230V$

Rated capacities $\left(S_{W_{1q}}, S_{W_{2q}}\right)$ for individual winding of this transformer:

$$S_{W_{1q}} = 397.9 \cdot 7.3 = 2904W,$$

$$S_{W_{2q}} = 229.6 \cdot 12.2 = 2801W.$$

Value S_q is slightly exceeded of S_p due to the fact that transformer "q" is additionally loaded by idling current of transformer "p".

Total capacity (S_{PST}) of two transformers elements forming the PST

$$S_{PST} = S_p + S_q = 2799 + 2852 = 5651W.$$

Dividing the value obtained $\left(S_{PST}\right)$ at the output power of device $\left(S_s = U_r I_r = 218,4 \cdot 12 = 2621W\right)$ we get the rated capacity of PST is $\dfrac{S_{PST}}{S_r} = \dfrac{5651}{2621} = 2.15$.

Thus, the rated capacity of PST in question is 2,15 times more of its output power. To justify the appropriateness of such bulky items will be very difficult.

Note also that value $S_{W_{1p}} = S_{W_{2q}} = 2801W$ describe the exchange of operating power between "p" and "q" transformers elements. This operating power also determines the rated capacity of Power Electronics, if it uses to control the PST. From the Table 3 follow that rated capacity of Power Electronics for such a device will be somewhat more than the output power of PST $\left(S_s = U_r I_r = 218,4 \cdot 12 = 2621W\right)$. Sure, it would require more substantial financial expenses.

Further we will consider some options for circuit realization of PST which allow to provide the less expensive designs.