LOW COST MATRIX CONVERTER BASED THREE PHASE TO SINGLE PHASE CONVERTER

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Abstract: : *This paper presents a new approach for converting three phase AC power to single phase using a simple circuit topology with bidirectional switches that are triggered by logically generated gating pulses. The phase converter chosen in this work involves single stage power conversion principle and is capable of providing a variable voltage, variable frequency but constant v/f single phase output voltage from available three phase source using Matrix Converter (MC). The proposed circuit topology is capable of operating a single phase AC motor under constant v/f mode eliminating the occurrence of negative sequence currents in the power system network as it tends to create balanced loading of all three phases. The performance of the chosen phase converter is evaluated in MATLAB/SIMULINK environment for different types of load. The real time implementation of MC based phase converter is also carried out using low cost but powerful TMS320F2407 DSP and the experimental results obtained are compared with those obtained through simulation. The results obtained validate the strategy developed. The significant application of this phase conversion technique is simplified feeder mechanism for electric locomotives.*

Key words: *Matrix Converter (MC), Three Phase to Single Phase Converter (TPSPC), Harmonics.*

1. Introduction

In many instances, the single phase load is supplied by one phase of three phase service when single phase service is not available. Supplying high power density single phase load like electric traction becomes prohibitive due to occurrence of higher negative sequence currents in the power grid which causes over heating of all devices connected to the grid. Therefore three phase to single phase converters [1-3] are excellent choice for situations where negative sequence currents are expected to be kept at minimum value. Hence TPSPC are used to energize the single phase feeder used for electric traction. The cost of TPSPC can be made economical as the cost of power semiconductor switches are decreasing and converter topologies with high device count are starting to draw more attention. The most important and valuable characteristic of these new topologies is that even under unbalanced and significantly disturbed input voltage waveforms, the output waveforms turn out to be reasonably clean and balanced. For this reason, several phase conversion systems [4-8] have been developed and are widely used.

Presently available TPSPC converters can be broadly classified into three categories:

a) Rotary type converters wherein single phase alternator is driven by three phase motor.

b) Cascaded static converters wherein three phase AC is converted to DC and then to single phase AC by single phase inverter.

c) Single stage direct phase converter using MC.

Categories (a) and (b) employ bulky magnetic components of considerable size and weight. Category (c) employs single stage conversion without need for high bulky magnetic components due to operation of bidirectional switching cell at high switching frequency.

2. Phase Conversion Using MC

The MC based three phase to single phase converter proposed in this paper employs only three bidirectional switching cells for phase transformation possessing following merits:

a) It allows for voltage control incorporating dual technique (phase conversion with chopping technique).

b) It also helps in frequency control in turn employing constant v/f control.

c) Resulting converter input current is nearly sinusoidal with approximate sinusoidal output current.

d) It results in balanced loading of all three phases resulting in elimination of negative sequence currents in the grid.

e) It provides simplified phase conversion technique.

The basic phase converter configuration shown in Fig.1 (a) can be operated in varying conduction angle mode resulting in voltage control.

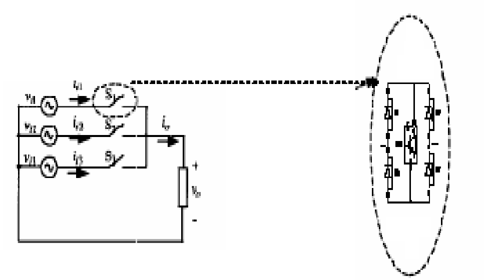


Fig. 1(a) Configuration of MC based three phase to single phase conversion system

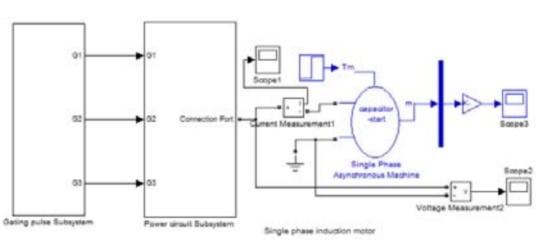


Fig.1 (b) Sub system configuration

An attempt is made in this work to model and simulate MC based three phase to single phase static converter fed induction drive. To simplify the simulation process, matrix converter based phase converter, load, measurement block and gating pulse generator are modeled as a subsystem shown in Fig.1 (b).

3. Analysis of MC based Phase Converter

MC chosen in this work converts a three phase AC voltage at supply frequency ω_i directly to single phase AC output voltage at either required amplitude V_o or frequency ω_0. It uses high frequency self commutated switching devices which are capable of conducting in both directions. The converter has a matrix of switching devices that permit the conversion of any input to any output which can be represented as

[1*1]=[1*3] [3*1]

Z = X * Y

where

X- Input voltage matrix

Y- Switching matrix

Z- Output voltage matrix

The operation of the proposed converter is based on the principle that multiplication of [1*3] sinusoidal quantity (input voltage matrix) by a compatible set of [3*1] converter switch matrix yields a third set of [1*1] sinusoidal quantity (output voltage matrix). Therefore the analytical equation for converter output voltage $[V_o(\omega_o t)]$ and input current $(I_i(\omega_i t)]$ can be obtained from following equations:

$$[V_0(\omega_0 t)] = [F_d(\omega_s t)][V_i(\omega_i t)]$$

$$= A\left[f_{1,1} \quad f_{1,2} \quad f_{1,3}\right]\begin{bmatrix} V_{i,1} \\ V_{i,2} \\ V_{i,3} \end{bmatrix}$$

$$= A\left[\cos(\omega_s t) \quad \cos(\omega_s t - 120) \quad \cos(\omega_s t - 240)\right]$$

$$* V_i \begin{bmatrix} \cos(\omega_i t) \\ \cos(\omega_i t - 120) \\ \cos(\omega_i t - 240) \end{bmatrix}$$

$$= \frac{3AV_i}{2}\left[\cos(\omega_s - \omega_i)t\right]$$

$$= \frac{3AV_i}{2}\left[\cos \omega_0 t\right]$$

where $\omega_s = \omega_0 + \omega_i = 2\omega_i = 2\omega_0$

$$[I_i(\omega_i t)] = [F_d(\omega_s t)]^T [I_o(\omega_o t)]$$

$$\begin{bmatrix} I_{i,1} \\ I_{i,2} \\ I_{i,3} \end{bmatrix} = A \begin{bmatrix} f_{1,1} \\ f_{2,1} \\ f_{3,1} \end{bmatrix} * \left[I_0 \cos(\omega_0 t)\right]$$

$$= A \begin{bmatrix} \cos(\omega_s t) \\ \cos(\omega_s t - 120\ ) \\ \cos(\omega_s t - 240) \end{bmatrix} \cdot * \left[I_0 \cos(\omega_0 t)\right]$$

The respective switch on/off control strategy and the resulting single phase output voltage are shown in Fig 2, for one half cycle of each phase whose switching frequency is f_{input}.

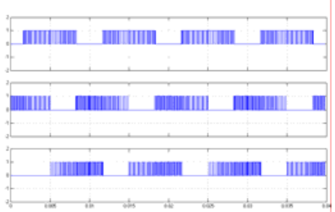


Fig.2 On/off control strategy and the resulting single phase output voltage

The essential information regarding the transfer characteristics of the proposed single stage TPSPC can be obtained by simulation using MATLAB/SIMULINK model developed for different types of load.

4. Gating Logic

For proper operation of TPSPC, it is essential to generate three gating signals for three bidirectional switching cells corresponding to three phase input of TPSPC i.e one gating signal for each bidirectional switch cell which can be pulses of either 120^0 or lesser. The three gating pulses are shown in Fig.3 which are produced by simple logic circuit elements. These gating pulses are applied directly to the gates of appropriate bidirectional switching cells through opto-isolators. Voltage control can be achieved by introducing notches either in the beginning or middle or end of these pulses or by varying pulse width or switching frequency.

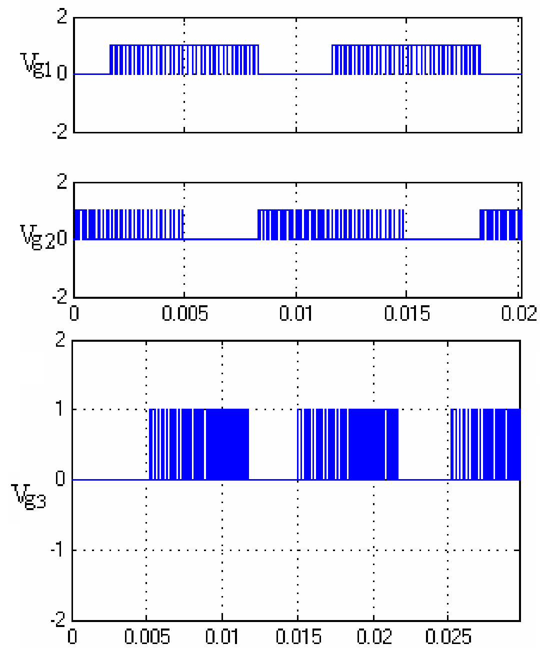


Fig.3 (a) Gating pulses (simulation)

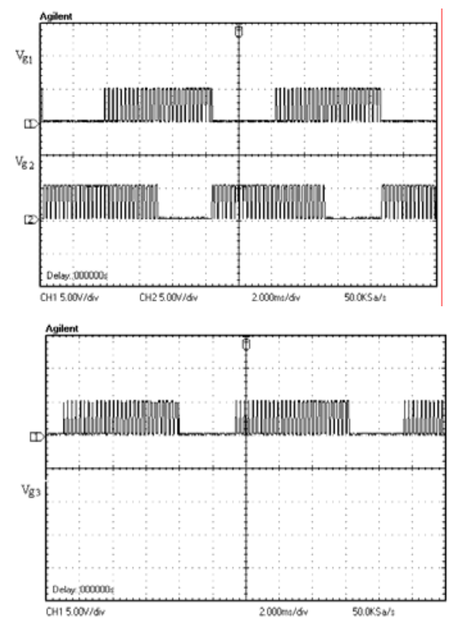


Fig.3 (b) Gating pulses (hardware setup)

5. Simulation Results

To demonstrate the feasibility of the proposed TPSPC, the results have been obtained through simulation for different types of load before realization in real time. Fig.4 shows the input current waveform. The output voltage and current waveforms and the frequency spectrum of output voltage for R (100Ω) , R-L (R=100 Ω, L=300mH) and motor loads are presented in Figs.5-10 for sample modulation index of 0.9 with switching frequency f_s= 5KHz .

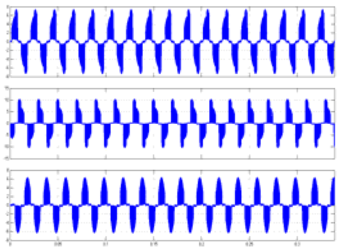


Fig.4 Input current waveform

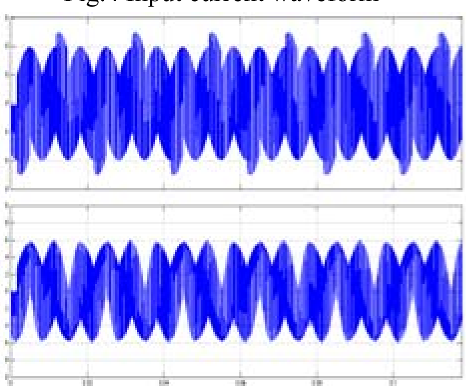
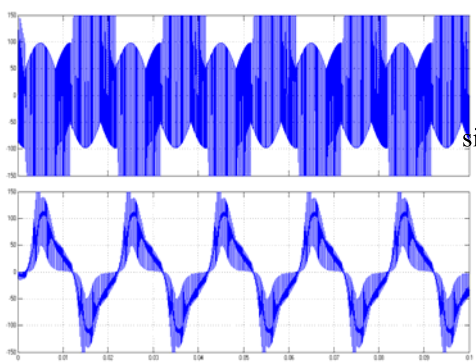


Fig.5 Simulated load voltage and current of MC based TPSPC (R load)



simulation

Fig.6 Simulated load voltage and current of MC based TPSPC (R-L load)

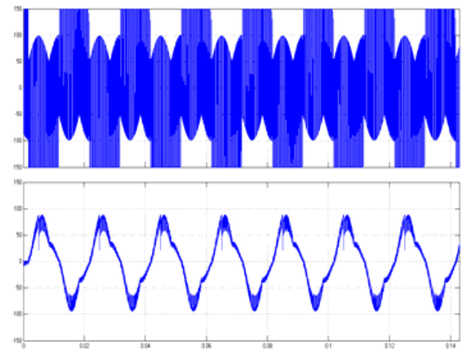


Fig.7 Simulated load voltage and current of MC based TPSPC (motor load)

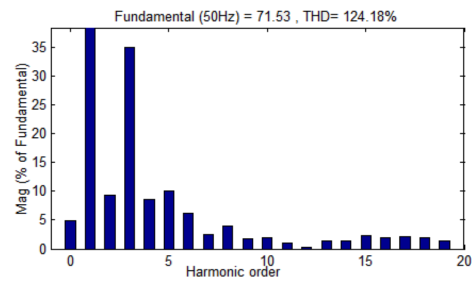


Fig.8 FFT of MC based TPSPC obtained through simulation (R load)

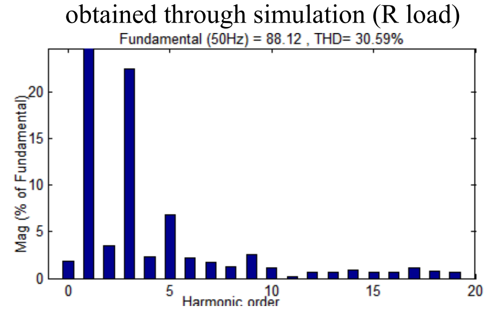


Fig.9 FFT of MC based TPSPC obtained through simulation (R-L load)

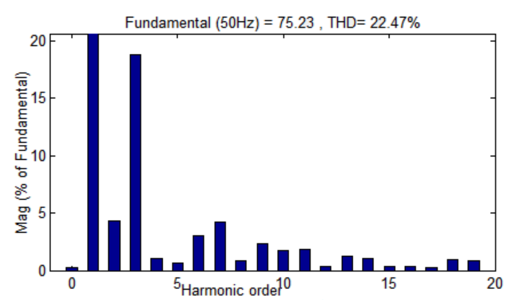


Fig.10 FFT plot of MC based TPSPC obtained through simulation for motor load

6.Experimental Setup

The system (Fig.11) consists of a three phase source that feeds single phase load through an input filter and switching matrix. The input filter comprises of an inductor and capacitor which are designed to reduce the input current ripple with minimum stored energy on the reactive elements and cut off frequency lower than the switching frequency.

The switching matrix comprising of semiconductor switches which are driven by DSP through gate drive circuitry from microcontroller/DSP does the function of phase conversion simultaneously maintaining the v/f ratio of output voltage constant to drive a single phase induction motor. Three switching cells were used for phase conversion. Each switching cell comprises of four diodes with single IGBT. Optocouplers were used to isolate each IGBT which is provided for each phase. Opto couplers have an inbuilt push pull output that offers a maximum of 1v low level output voltage which eliminates the need for negative gate drive.

The 3ϕ 400v supply is stepped down to 110v using step down transformer and is used as a source for the proposed converter. Instead of sensing the phase voltages v_A , v_B and v_C the line voltages v_{AB} and v_{BC} were sensed and by using software algorithm v_A , v_B and v_C were computed. Sensing is done using two potential transformers . A low value resistor in series with the load was used to sense output current.

The clamp circuit provided in the proposed converter is an important component. The main use of this circuit is to provide a path for the commutation of energy stored in the leakage inductance of load. Under a fault condition all switches in the converter are immediately turned off so that the clamp serves to deenergize the load current without damaging the power switches. The clamp circuit used comprises of dual circuit pack diode rectifiers with a capacitor on input side and another for output side. Appropriate capacitor has been chosen depending on the load current, load inductance and the highest allowable capacitor voltage in this work.

By controlling analog circuits digitally, system costs and power consumption can be drastically reduced. DSPs usually include on-chip PWM controllers, making implementation easy. Hence the real time implementation for chosen TPSPC using TMS320LF2407 DSP is carried out in this work. The output voltage and current waveforms along with harmonic spectra of output voltage for both linear and non-linear loads are presented and analyzed.

Overview of TMS320LF 2407 DSP

The Texas Instruments' TMS320LF2407 DSP is a programmable digital controller with C2xx DSP as the core processor. The DSP core is a 16-bit fixed point processor. It contains on-chip memory and useful peripherals integrated onto a single piece of silicon. The speed of operation is 40 Million Instructions Per Second (MIPS). The high processing speed of C2xx CPU allows user to compute parameters in real time. The following characteristics make this DSP the right choice for a wide range of applications:

- Very flexible instruction set
- Inherent operational flexibility
- High speed
- Innovative parallel architecture
- Compactness and cost effectiveness

The peripheral set includes:

- Two event managers (A and B)
- General purpose timers
- PWM generators for digital motor control
- Analog to digital converter
- Control area network interface
- Serial peripheral interface – synchronous serial port
- General purpose bi-directional digital input/output pins
- Watch dog timer ("time-out" reset device for DSP system integrity)

A resistance divider scales down the output voltage suitably in a signal conditioning circuit. The output voltage of the signal conditioning circuit is fed to the ADC of DSP through a high impedance differential input amplifier. The DSP suitably adjusts the amplitude of the modulating signal such that v/f ratio at the output of converter remains constant and generates PWM pulses to be applied to the gates of IGBTs through optocoupler and IGBT driver circuits. The event manager module of the DSP is programmed to provide the PWM signal suitable for constant v/f mode operation.

A prototype model of TPSPC (Fig. 11) was developed and tested with resistive, inductive and single phase induction motor loads. The output voltage with above loads are shown in Figs.12-14. Next three figures (Figs. 15-17) show corresponding currents. Figs.18-20 display FFT of the output voltage only for above loads. For R-L load spikes are noticed in the current waveform. The waveforms are obtained using Digital Storage Oscilloscope (DSO) with 10:1 probe.

Fig. 11 Hardware setup

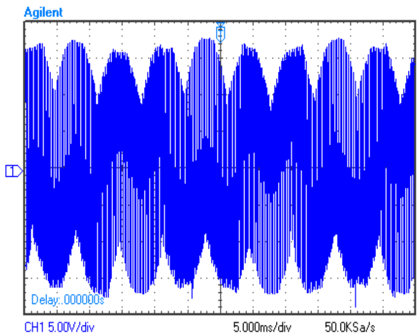


Fig.12 Experimental load voltage of MC based TPSPC (R load)

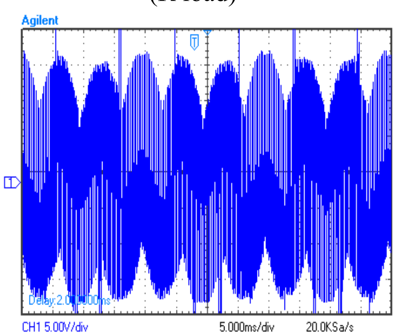


Fig.13 Experimental load voltage of MC based TPSPC (R-L load)

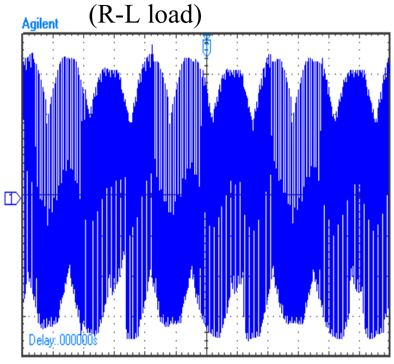


Fig.14 Experimental load voltage of MC based TPSPC (motor load)

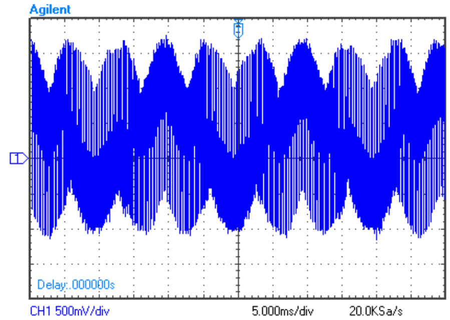


Fig.15 Experimental load current of MC based TPSPC (R load)

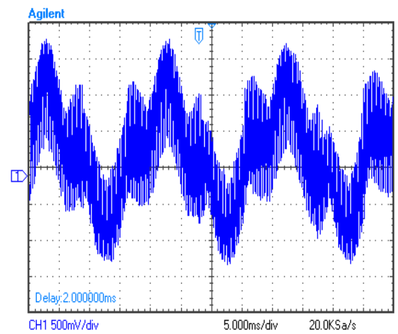


Fig.16 Experimental load current of MC based TPSPC (R-L load)

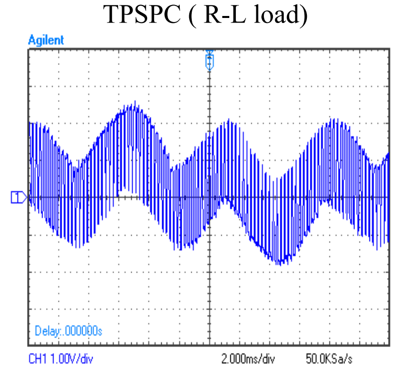


Fig.17 Experimental load current of MC based TPSPC (motor load)

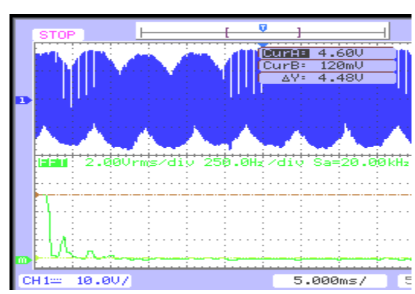


Fig.18 FFT of experimental output voltage of MC based TPSPC (R load)

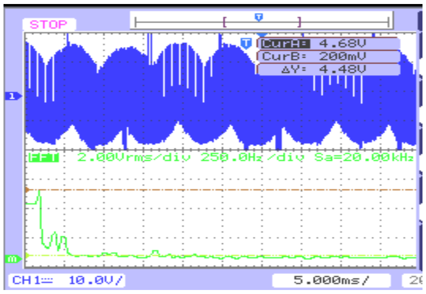


Fig.19 FFT of experimental output voltage of MC based TPSPC (R-L load)

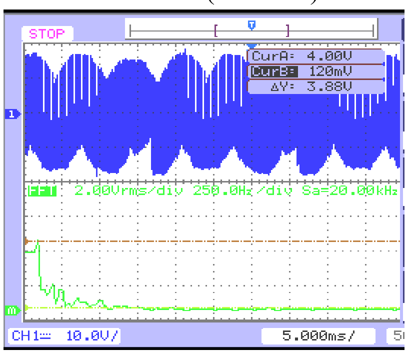


Fig.20 FFT of experimental output voltage of MC based TPSPC (motor load)

Tables 1-3 provide details of FFT analysis of output voltage with three chosen types of load fed by TPSPC. Next table compares THD of load voltage for various modulation indices for the above loads.Tables 5-7 provide details of power factor analysis of output voltage with three chosen types of load fed by TPSPC.

Table 1 FFT analysis of output voltage for R load

Modulation index	Fundamental value(volts)	THD(%)
0.9	70.7	1.43
0.8	65.9	2.23
0.6	56.6	3.25

Table 2 FFT analysis of output voltage for R-L load

Modulation index	Fundamental value(volts)	THD(%)
0.9	66.6	1.30
0.8	59.9	1.61
0.6	56.3	2.08

Table 3 FFT analysis of output voltage for motor load

Modulation index	Fundamental value(volts)	THD(%)
0.9	56.5	1.36
0.8	51.9	1.65
0.6	42.4	2.67

Table 4 Comparison between R load, R-L load and motor load

m_a	R load THD(%)	R-L load THD(%)	Motor load THD(%)
0.9	1.43	1.30	1.36
0.8	2.23	1.61	1.65
0.6	3.25	2.08	2.67

Table 5 Power factor variation for R load

Modulation index	Angle between v and i	Power factor
0.9	0	1
0.8	0	`1
0.6	0	1

Table 6 Power factor variation for R-L load

Modulation index	Angle between v and i	Power factor
0.9	41.4	0.75
0.8	55.8	0.5621
0.6	72.0	0.309

Table 7 Power factor variation for motor load

Modulation index	Angle between v and i	Power factor
0.9	25.2	0.90
0.8	50.4	0.60
0.6	57.6	0.54

7. Conclusion

Analysis of a phase conversion technique which is capable of providing single phase power from existing three phase mains has been presented in this paper. The proposed converter provides single phase output with low THD which can be confirmed from results. The simple control logic circuit makes the proposed converter highly attractive. The simulated results obtained using MATLAB/SIMULINK model prove the validity of the model which is also implemented in real time. Hardware results show that THD is within permissible levels. Hence the switching strategies developed for TPSPC is validated for R, R-L and motor loads.

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