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Fuzzy Self-tuning PI Controller for Phase-Shifted Series Resonant Converters

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Abstract- **A linearized model of the phase-shifted series resonant converter is necessary for closed loop design. With fixed PI control design, the converter does not have good disturbance rejection capability and cannot always cope with a wide range of uncertainties. In this paper, a PI self-tuning mechanism based on a fuzzy logic scheme is proposed. It corrects the PI gains, initially designed using small-signal modeling, to improve converter dynamic response and disturbance rejection. The algorithm is based on continuous change/adaptation of the PI gains until best dynamic response is achieved. Simulation results compare responses for the PI fixed parameters with the fuzzy-adapted controller gains under different disturbance conditions.**

NOMENCLATURE

v_g	DC supply voltage (V)
i_L	Resonant tank inductor current (A)
v_C	Resonant tank capacitor voltage (V)
v_{AB}	Inverter Output voltage (V)
v_p	Transformer primary voltage (V)
v_s	Transformer secondary voltage (V)
n	Transformer turns ratio
L	Resonant tank inductance (μH)
C	Resonant tank capacitance (μF)
C_o	Output filter capacitance (μF)
v_o, i_o	Output voltage and current respectively (V,A)
R_L	Load Resistance (Ω)
f_s	Inverter switching frequency (kHz)
f_o	Resonant frequency= $1/2\pi\sqrt{LC}$ (kHz)
δ	Phase-shift angle between inverter legs (rad)
v_{oref}	Desired output voltage (V)
k_e	Error normalizing coefficient
k_v	Output voltage derivative normalizing coefficient
e	Controller error signal= $v_{o_{ref}} - v_o$ (V)
e_n	Normalized error signal
$\dot{v_{o_n}}$	Normalized output voltage derivative
$k_p{}^*, k_i{}^*$	Initially designed PI controller gains obtained through small-signal analysis
$\Delta k_p, \Delta k_i$	Change in PI controller gains (outputs of fuzzy logic algorithm)
k_p, k_i	Corrected PI controller gains

I. INTRODUCTION

THE NON-LINEAR control nature of the series resonant converter (SRC) has lead to the development of several linearized small-signal models for analysis, stability studies and closed-loop control design [1,2]. Discrete time-domain modeling approaches [3-5] and multiple frequency averaged modeling [6-9] have been proposed. These models have aided in closed-loop control design, but with fixed-parameter controllers designed for a certain steady-state operating point of the SRC. With the non-linear nature of the converter, and the constantly changing steady-state operating point due to supply fluctuations, load variances, component tolerances and external disturbances, fixed-parameter controllers may eliminate error in output but the dynamic performance may not be satisfactory.

Advanced control strategies have been developed in literature to improve the performance of dc/dc converters [10-12], but they depend on the plant model accuracy. Adaptive control techniques for phase-shifted SRC have been reported in literature such as auto disturbance rejection control [13] and passivity based control [14]. A quasi current mode control for phase-shifted SRCs has been proposed in [15]. It depends on regulating the rectified resonant current to improve the converter dynamic performance. Robust controllers for series resonant inverters have also been implemented in literature. A load adaptive control algorithm for series resonant inverters used for domestic induction heating has been proposed in [16]. The algorithm is composed of several modulation techniques; square wave variable frequency modulation and pulse density modulation. A comparative study of sliding mode control schemes for series resonant inverters with quantum modulation is reported in [17]. Sliding mode control systems provide both low sensitivity to disturbances and simple design given by reduced order dynamics.

Most of the above controllers, although superior to conventional PI types, need either an accurate plant model or a reliable instrumentation scheme. Fuzzy logic controllers, however, do not. PI gains adjustment can be done by a scheme based on fuzzy logic algorithm. In order to account for sensor noise, model uncertainties and shifts in operating points, the linguistic characteristics of fuzzy control provide a very good approach to the uncertainty problem. Fuzzy rules derivation, by principle, relies on the experience of human expert [18]. This paper presents a fuzzy logic based approach for PI self-tuning of phase-shifted SRC. Initial values for PI controller gains $k_p{}^*$, $k_i{}^*$ are designed by linearization of the SRC small-signal model around a specific operating point. A fuzzy logic algorithm is then designed for controller parameter adaptation to improve dynamic response and disturbance rejection.

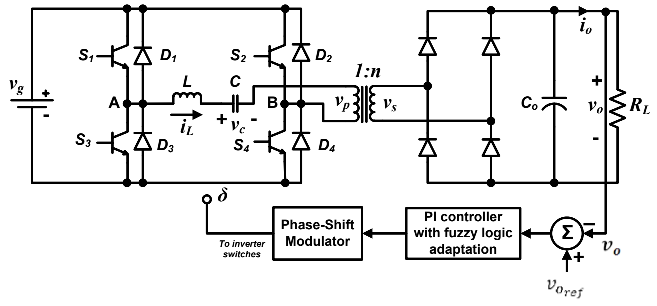


Fig. 1. Closed loop control configuration for phase-shifted SRC.

II. SYSTEM DESCRIPTION

Fig. 1 illustrates the closed loop control architecture for the phase-shifted SRC. The system is simulated using switching models for the power electronic converters together with control environment in Simulink/Matlab software for the closed loop system. Initial design of the controller PI gains $k_p{}^*, k_i{}^*$ is carried out using small-signal model of SRC. This is briefed in section III and detailed in [19]. A fuzzy logic scheme is used to self-adapt the PI controller gains according to system output for best dynamic response and disturbance rejection. Details of the fuzzy logic control structure are discussed in section IV.

III. INITIAL PI CONTROLLER DESIGN USING SMALL SIGNAL ANALYSIS

Small-signal analysis of SRCs has been extensively covered in literature. This section only briefs the use of discrete time domain small-signal modeling in closed loop design of phase-shifted SRCs. This is fully detailed in [19]. State-plane analysis is first used to derive a generalized state-space model for the phase-shifted SRC. This model is discretized, normalized, perturbed and linearized around a specific operating point to obtain the small-signal model. The control parameter is the phase shift angle δ. A generalized small-signal state-space model results in the form of,

$$\hat{x}(k+1) = A\hat{x}(k) + B\hat{\delta}(k) \tag{1}$$

where,

$\hat{x}(k) = [\hat{\imath}_L \quad \hat{v}_c \quad \hat{v}_o]^T =$ State-vector of small-signal model with perturbed state variables,

$A =$System small-signal matrix, and

$B =$Small-signal Input vector.

Hence, a small-signal transfer function of phase-shift to output voltage can be obtained,

$$T_p(s) = \frac{\hat{v}_o(s)}{\hat{\delta}(s)} = [0 \quad 0 \quad 1][zI - A]^{-1}B \tag{2}$$

The closed loop configuration in Fig.1 can, therefore, be illustrated in terms of control systems as shown in Fig.2.

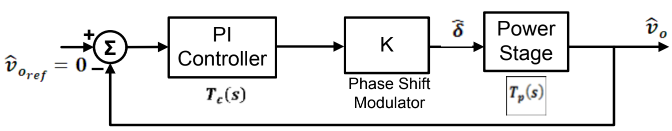


Fig. 2. Small-signal closed loop control structure for phase-shifted SRC.

By selecting a certain operating point with specified loading conditions, the PI controller $T_c(s)$ can de designed using Bode plot analysis as in [19]. $T_c(s)$ takes the form,

$$T_c(s) = k_p{}^* + \frac{k_i{}^*}{s} \tag{3}$$

where,

$k_p{}^*, k_i{}^*$ are the PI controller gains initially designed at a given operating condition. The fuzzy-logic scheme is used to improve system dynamic response, by producing a change around these initial values, as the operating conditions change and external disturbances apply.

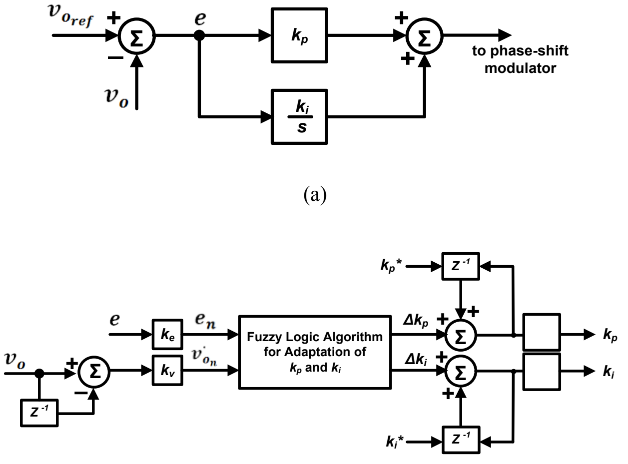
IV. FUZZY LOGIC CONTROL DESIGN

This section details the design of the rule-based fuzzy logic controller used to improve the transient response of the SRC via PI controller gains adaptation. The inputs to the fuzzy controller are the normalised error signal e_n and normalised output voltage derivative $\dot{v}_{o_n}$. The fuzzy controller state variables are the fuzzy sets associated with e_n and $\dot{v}_{o_n}$. The fuzzy controller outputs are the accumulated changes in the proportional and integral gains $(\Delta k_p, \Delta k_i)$ from initial designed values $k_p{}^*$ and $k_i{}^*$. This is obtained via feedback of corrected gains (k_p, k_i) as shown in Fig. 3b. k_p and k_i are the actual PI gain values in the voltage feedback loop (Fig. 3a). The fuzzy procedure assumes that controller gains variation span is a limited range. The limits of k_p and k_i are determined using the stability limits of the system from the small-signal analysis in the previous section.

A. Fuzzification Algorithm and Fuzzy Control Rules

The two inputs are e_n and $\dot{v}_{o_n}$.

- The 'normalized error variable' has three linguistic values with their associated fuzzy sets: error positive (ep), error zero (ez) and error negative (en).
- Similarly, the 'normalized output voltage derivative': derivative positive (dp), derivative zero (dz) and derivative negative (dn).



(a)

(b)

Fig. 3. (a) General layout of closed loop controller, (b) Fuzzy tuning mechanism for PI controller gains.

The two controller outputs are Δk_p and Δk_i.

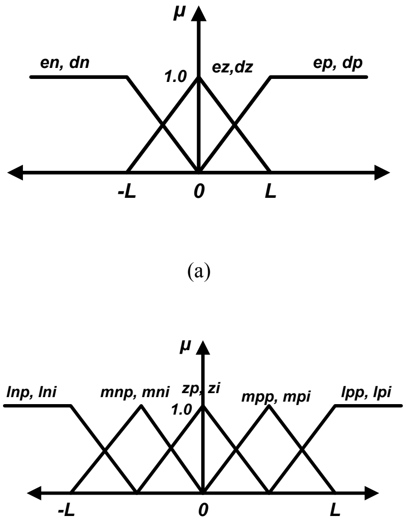
- The 'change in proportional gain' output has five fuzzy sets: large positive proportional (lpp), medium positive proportional (mpp), zero proportional (zp), medium negative proportional (mnp) and large negative proportional (lnp).
- Similarly, the 'change in integral gain' output: large positive integral (lpi), medium positive integral (mpi), zero integral (zi), medium negative integral (mni) and large negative integral (lni).

Five membership functions were chosen for the fuzzy controller outputs to provide the appropriate change in PI gain in accordance with change in output response. This ensures gradual and smooth tuning of the PI controller gains to avoid closed loop instability.

The membership grades for the fuzzy controller input and output variables are shown in Fig. 4. They are chosen to be triangular and symmetrical. L in the figure denotes maximum error or maximum output voltage derivative multiplied by their normalizing gains k_e and k_v respectively. Limits L for the output sets (Δk_p and Δk_i) are obtained from the small-signal stability analysis described in section III. μ is the membership degree of the fuzzy set members. The fuzzy rules in Table I summarise the set of implemented fuzzy control rules. Nine fuzzy control rules exist with an implied AND operation between the two consequent parts. An example is given by,

Rule 1: If e_n is ep AND $\dot{v}_{o_n}$ is dp THEN Δk_p is zp AND Δk_i is zi. (4)

Rule 2: If e_n is ep AND $\dot{v}_{o_n}$ is dz THEN Δk_p is mpp AND Δk_i is mpi. (5)



(a)

(b)

Fig. 4. Membership grades of: (a) inputs (Normalized error and output derivative) and (b) outputs (change in k_p and k_i gains).

TABLE I
FUZZY RULE TABLE

$\dot{v}_{o_n}$ \ e_n	ep	ez	en
dp	zp	mpp	lpp
dz	mpp	zp	mpp
dn	lpp	mpp	zp

(a) Δk_p

$\dot{v}_{o_n}$ \ e_n	ep	ez	en
dp	zi	mpi	lpi
dz	mpi	zi	mpi
dn	lpi	mpi	zi

(b) Δk_i

The fuzzy control rule design has been performed according to basic control knowledge of diverging and converging system responses without any mathematical plant model. While designing the rule-base, the following important factors have been taken into account [18],

- When error is largely positive with negative output voltage rate (or vice versa), the system is diverging away from the equilibrium point and a large positive increase in controller gains is required.
- When error and output voltage rate are both positive (or vice versa), the system is converging toward the equilibrium point. Controller action should be minimised to prevent the system from oscillating further, hence, lowering the values of the controller gains.
- For small/zero values of the error and its derivative, the system is assumed to be near the equilibrium point. Therefore, the controller should operate with the nominal values of the gains, which is manifested as zero change in the gains in the rule table.

B. Fuzzy Inference Engine (Implication and Aggregation)

The inference engine of the fuzzy logic controller matches the preconditions of rules in the fuzzy rule base with the input state linguistic terms and performs implications [20]. The firing strengths $\alpha_1, \alpha_2 \ldots . \alpha_9$ of the rules 1 to 9 are obtained using Zadeh AND operation i.e. performing a T-norm with *min* operator. For example, for a given error and output derivative,

$$\alpha_1 = \min(\mu_{ep}, \mu_{dp}),\ \alpha_2 = \min(\mu_{ep}, \mu_{dz}) \text{ and so on} \qquad (6)$$

A *min* implication is then performed followed by a *max* aggregation. According to Zadeh, this is known as a *min-max* aggregation. An illustrative example of the procedure is shown in Fig. 5 using only the first two rules. However in real control, all nine rules are involved in calculation.

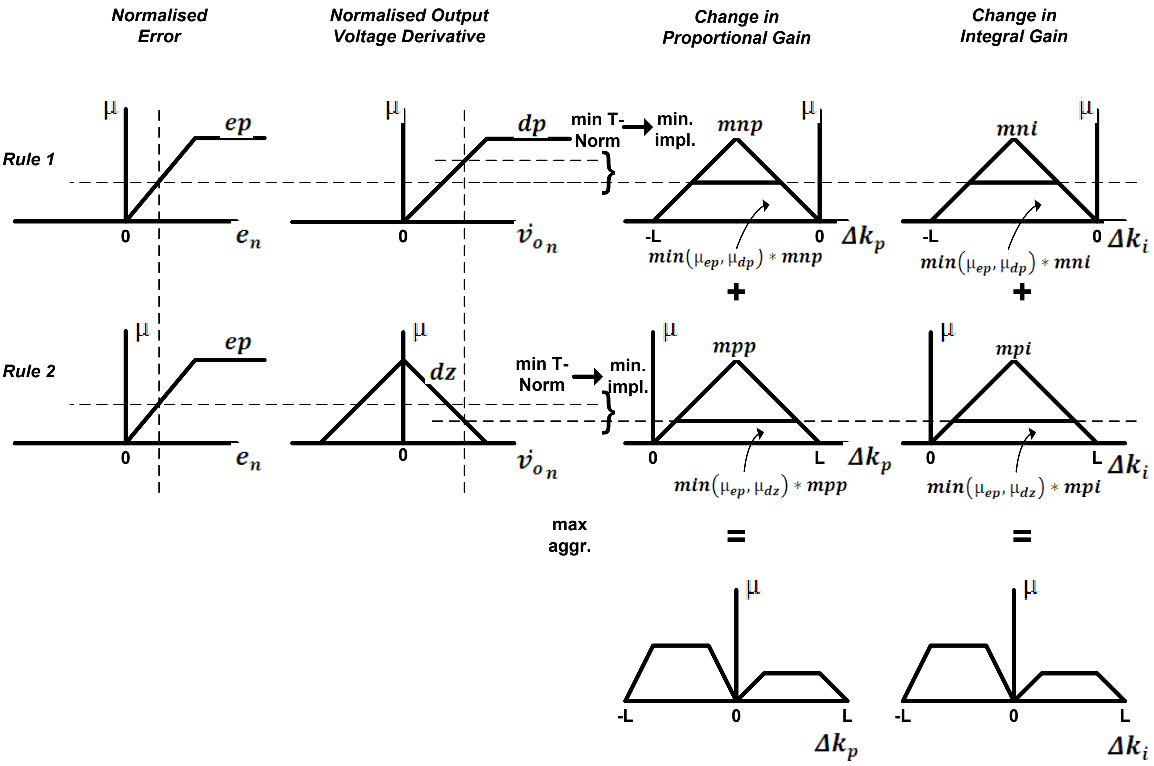


Fig. 5. A graphical presentation of a rule-based inference procedure.

C. Defuzzification

The result of fuzzy inference is a fuzzy output set. Defuzzification extracts the crisp output value from the resultant output fuzzy set. Controller crisp output values for Δk_p and Δk_i are calculated using the *centroid* method or the *center of area (COA)* principle,

$$y = \frac{\sum \mu_i y_i}{\sum \mu_i} \tag{7}$$

where, y represents the crisp value of the fuzzy controller output (Δk_p or Δk_i), y_i is a discrete element of an output fuzzy set, and μ_i is its membership grade.

V. RESULTS AND DISCUSSION

The phase-shifted SRC closed loop voltage control (Fig. 1) is implemented in Matlab/Simulink software. Simulation parameters are summarised in Table II. The initially designed PI controller gains (from small-signal analysis) are $k_p^* = 5$ and $k_i^* = 1000$. Closed loop step response of the system is assessed as follows:

- Light load to heavy load transition with no supply voltage disturbance (Fig. 6).
- Light load with supply voltage disturbance (Fig. 7).
- Heavy load with supply voltage disturbance (Fig. 8).

Results show that for both light and heavy loads, the fuzzy-adapted algorithm has improved the system dynamic performance in response to a sudden supply voltage change. Output voltage settling time is lower with the adapted scheme compared with the fixed initially designed PI parameters. Although the quicker response has been a result of higher gains applied, overall system stability is not reduced and steady state output is not oscillatory. This can be explained from the fuzzy logic rule-base since as the system reaches equilibrium ($e_n = 0\ and\ \dot{v}_{o_n} = 0$) the controller outputs ($\Delta k_p, \Delta k_i$) are zero and hence the PI gains stabilize on equilibrium values just reached. In addition, the converter responds in a quick and stable manner to the light-to-heavy load transition. The transient response of the output voltage at the start of the simulation is determined by the SRC output filter time constant $\tau = R_L C_o \simeq 1\,ms$.

TABLE II
SIMULATION VALUES

Parameter	Value
DC supply voltage, v_g	100V (initially) 70V (after transition)
Resonant tank inductance, L	100 µH
Resonant tank capacitance, C	0.28 µF
Resonant frequency, f_o	30 kHz
Inverter Switching frequency, f_s	40 kHz
Transformer turns ratio, n	1
Output filter capacitance, C_o	100 µF
Load Resistance, R_L	188.5 Ω (light) 9.425 Ω (heavy)
Desired output voltage, $v_{o_{ref}}$	30 V

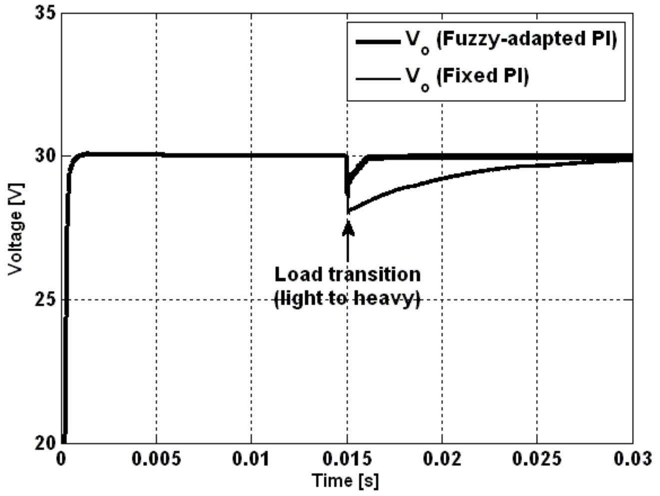


Fig.6. Closed loop step response of phase shifted SRC; light to heavy load transition.

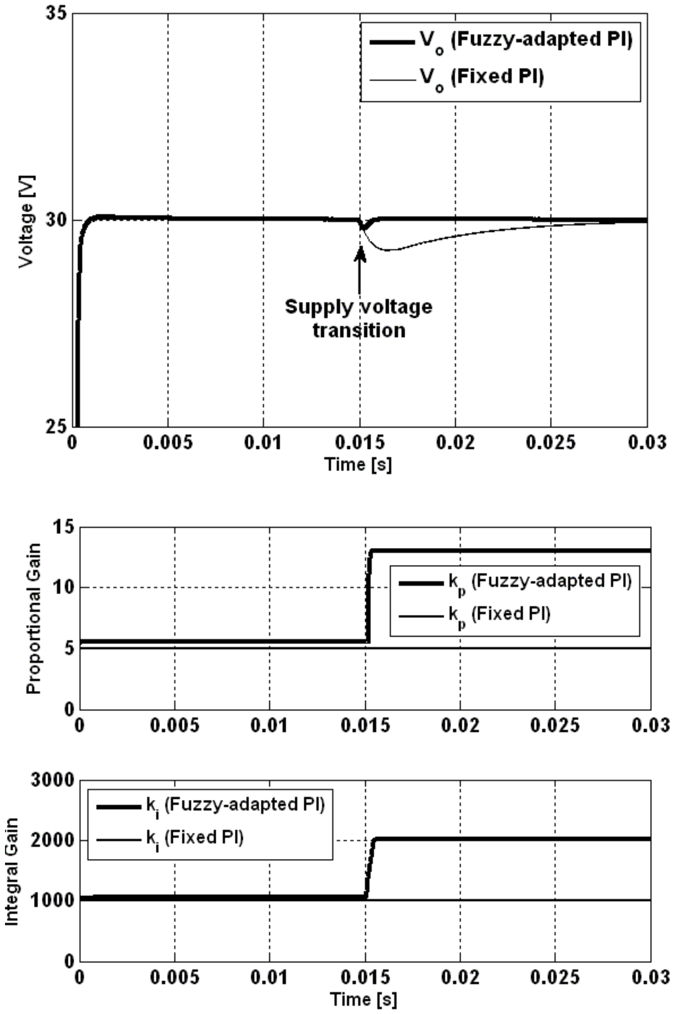


Fig.7. Closed loop step response of phase shifted SRC; light load with supply voltage disturbance

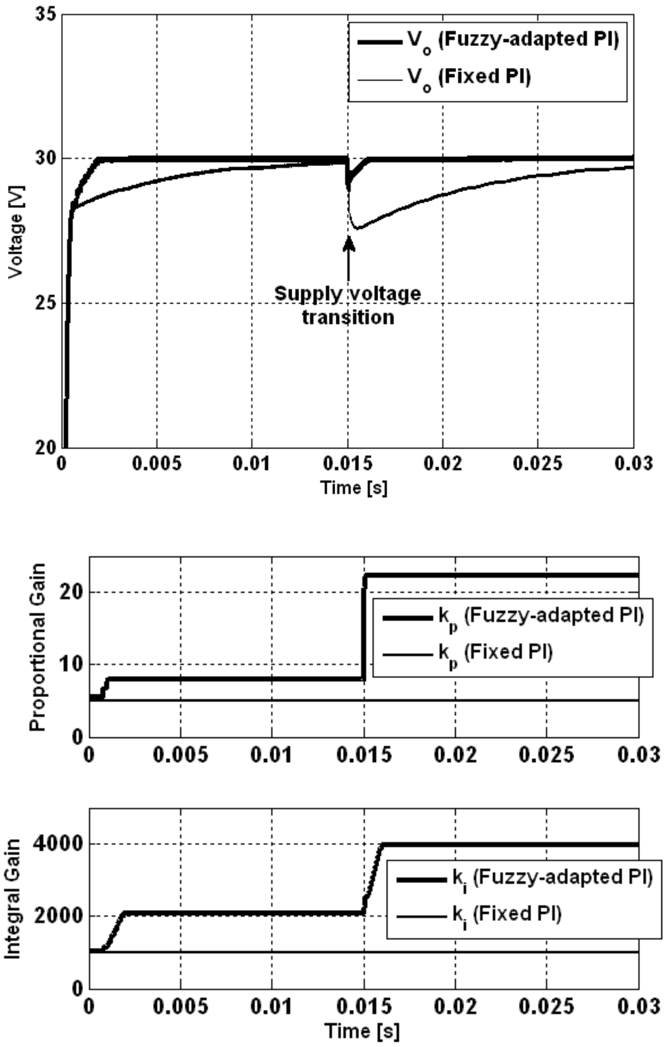


Fig.8. Closed loop step response of phase shifted SRC; heavy load with supply voltage disturbance

CONCLUSION

A self-tuning PI controller has been designed based on fuzzy logic scheme. The latter is designed according to basic control knowledge of closed loop systems. The proposed fuzzy logic scheme uses the normalised error and output voltage normalised derivative to provide an accumulative change in PI controller gains initially designed using small-signal analysis. Since the initially designed gains give best response at the operating conditions they were designed at, a controller with adaptive nature is needed to correct the PI gains as operating conditions change. The fuzzy logic algorithm performs this function. Results show that the fuzzy-adapted PI scheme improved converter transient response in terms of lower settling times for output voltage in response to different disturbances. Though PI gains are increased to satisfy the quicker response, system stability has not been affected and steady state output is not oscillatory. The paper verifies the robustness and simplicity of fuzzy logic algorithms in control systems with adaptive gain requirements.

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