Quasi Z Source Inverter Fed V/f Controlled Five Phase Induction Motor Drive Powered

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Abstract – **Impedance Source Inverters are extremely popular these days. They offer simultaneous boosting of input voltage applied as well as inversion operation. The converter achieves this by means of a specially designed impedance network along with H - Bridge. Unlike conventional H – Bridge (HB) inverters, impedance source inverters can boost the supply voltage thereby achieving boost operation. Utilizing this feature, voltage transient due to gird side disturbance, improved control and enhanced fault tolerance capability can be achieved. There are two types of impedance source-based inverters namely Z Source Inverters (ZSI) and quasi Z Source Inverters (qZSI). In this paper, five phase qZSI fed five phase induction motor drive is discussed. V/f control is implemented to induction motor in synchronism with closed loop voltage control of quasi network output voltage. Constraints in the integrated performance are discussed and taken into consideration for development of control algorithm. Simulation results are presented for the system when subjected to different load transients thereby validating the integrated control.**

Keywords: Five phase Induction motor drive, V/f control, quasi Z Source Inverter, Shoot through duty cycle.

I. INTRODUCTION

Modern drive systems usually consist of electric motor controlled by means of power converter. Analog or digital control is embedded with the system to achieve desired response. In addition to this, signal conditioning circuits are added to the system to achieve closed loop control. Three phase systems are preferred when compared to single phase because of higher efficiency, lower rating of individual components, easier control, balanced operation, fault tolerant capability etc. As a result, three phase systems are commercially available and most suitable for industrial applications. However, in applications where a machine is not readily available, multiphase machines are preferred because of the following advantages: possibility of splitting the required per-phase power rating, significant improvement in fault tolerance capability of the drive, sinusoidal input current, reduced torque pulsation and better noise characteristics. However, it also suffers from drawbacks of customized machine design and readily available three phase grid supply [1-3].

Five phase induction motor drive fed from voltage inverter is introduced way back in 1969. For the next two decades, there has been limited research in this area. But from early 2000s, development of application specific electric drives where the three-phase grid is not readily available (ship propulsions, aircrafts), led to accelerated growth and research in this area. PWM techniques have been developed and tested for desired operation of inverter fed multiphase machine drives [4-5]. Modelling of five phase induction motor is reported in literature by using the dynamic equations based on the circuit operation [6]. Advanced optimization techniques have also been reported to improve drive performance and fault tolerance capability [7]. Common mode voltage reduction techniques are also discussed in the literature [8].

Conventionally, two level inverters fed from a fixed voltage source are used to power the five phase machine drives. Control of these drives is achieved by varying the modulating signal, which is used for switching pulse generation by simple comparison with triangular carrier signal. However, with the new breed of impedance converters it is possible to control the input voltage to the inverter by means of impedance network. This feature in renewable energy applications eliminates the need for additional dc-dc converter [9-10].

qZSI consists of two capacitors , two inductors and one semiconductor diode followed by the conventional H Bridge. In conventional inverters, shorting of leg is avoided by introducing delay time in between incoming and outgoing switches. However, in impedance source-based inverters, this feature is utilized to boost the input voltage. By varying this period, it is possible to control the voltage boost. Different techniques of switching have been reported in literature to achieve the desired performance along with voltage boost [11-12]. Energy Efficient qZSI, component optimization and application of advanced control techniques are also discussed in the literature [13-15]. For renewable energy applications, grid connected qZSI are also developed. Their integration with different conventionally existing techniques is also discussed to suggest improvement of response and cost optimization [16]. Multilevel qZSI is also reported in the literature which improves the harmonic performance of the inverter along with reduced rating per switch as well increases the fault tolerance capability [17-18].

In this paper, five phase qZSI is used to control V/f operation of five phase induction motor. The system description is discussed in Section II. V/f control of induction motor is achieved by controlling its speed during starting and transients. Control algorithm is discussed in detail in Section III. Simulation results which validates the control are discussed in Section IV. Finally, summarized conclusions are presented in Section V.

II. SYSTEM DESCRIPTION

The system under investigation comprises of five phase induction motor powered by five phase qZSI as shown in Fig. 1. Input to qZSI is dc in nature.

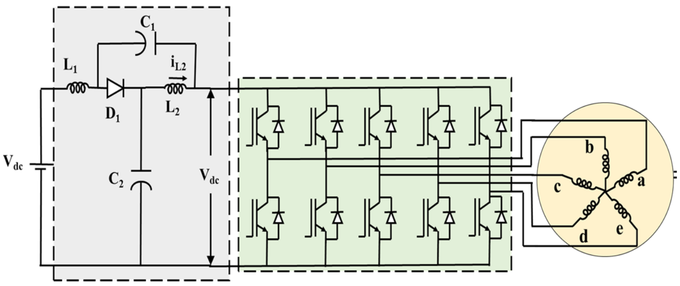


Fig. 1 – Five Phase Induction Motor powered with qZSI

a) *Five Phase qZSI:*

Quasi network consists of two inductors, two capacitors and one semiconductor diode. Here, input voltage applied can be boosted to desired value. This boosting is achieved by simultaneous shorting of all the inverter legs for a short period of time. This duration is called as Shoot through duty cycle (D) of qZSI. Operation of the qZSI can be segregated into two modes namely powering and shoot through mode as depicted in Fig. 2(a) and 2(b) respectively.

i) *Shoot through Mode*

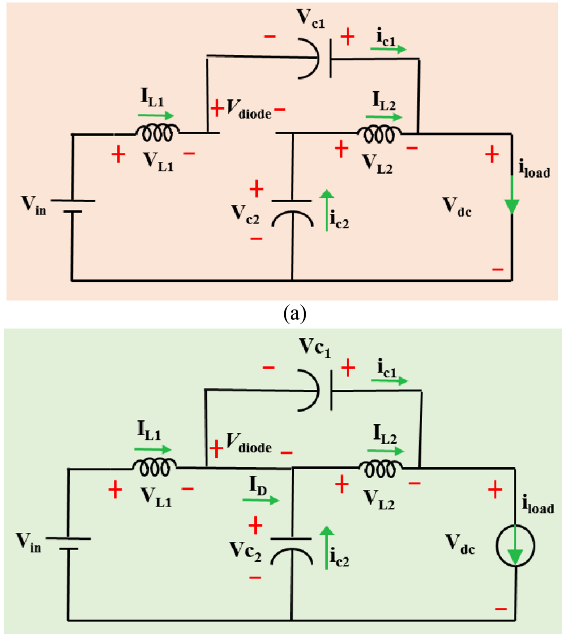
During this mode, all the inverter legs are shorted by simultaneous application of switching pulse to both the switches of the same leg. The Inductors are charged during this mode and the output voltage of the quasi network is zero. During this mode, the input voltage and voltage across the inductors are opposite in nature. Due to this, the voltage across the diode is negative and hence it is reverse biased. The current during the shoot through mode is shared between the five legs of the inverter.

Applying KVL to the circuit we get:

$$V_{diode} = V_{in} - V_{c2} - V_{L1} \quad (1)$$

Applying KCL to the circuit:

$$I_{L1} = I_{c1} \text{ and } I_{L2} = I_{c2} \quad (2)$$



(a)

(b)

Fig. 2 Equivalent circuit during (a) Shoot through Mode (b) Powering Mode

ii) *Powering Mode*

This mode is like the operation of conventional inverter. During this mode, the current flowing through the inductors decreases and hence the diode gets forward biased due to change in polarity of $L\frac{di}{dt}$. The energy stored in the inductors will charge the capacitors and the output voltage of the quasi network will be higher than the input voltage.

Applying KVL to the circuit:

$$0 = V_{in} - V_{c1} - V_{L1} \quad (3)$$

Applying KCL to the circuit:

$$I_{L1} + I_{c2} = I_{L2} + I_{c1} \quad (4)$$

Ratio of shoot through mode to the period of switching cycle is defined as shoot through duty cycle (D). Simplifying the above equations, the relations of the circuit can be given by:

$$V_{C2} = \frac{1-D}{1-2D} V_{in};\ V_{C1} = \frac{D}{1-2D} V_{in};\ V_{dc} = \frac{V_{in}}{1-2D} \quad (5)$$

where, shoot through duty cycle $D = \frac{T_0}{T_s}$

T_0 = Shoot through duration and T_s = Switching Cycle duration.

b) *Five Phase Induction Motor*

Five legs of qZSI feeds the five phase Induction motor. Phase Shift in the applied input voltage and spatial displacement of the five-winding construction ensures the operation of five phase Induction motor. Mechanical load is connected to the shaft of the motor. Speed sensor senses the speed of the motor and it is given as input to the control loop.

III. CONTROL ALGORITHM

The control structure is elaborated in Fig. 3. Control algorithm consists of V/f control of five phase induction motor and dc voltage control of qZSI. These two sections are described below in detail:

i) *V/f Control of Five Phase Induction Motor*

Speed reference of the motor (designated by ω_m^*) is compared with the sensed mechanical speed of the motor. The error is passed through to the controller to give slip speed (ω_{sl}). The mechanical speed is converter to electrical speed by multiplying with no. of pole pairs. This electrical speed is added to the slip speed to give synchronous speed. The ratio of rated voltage to the rated frequency (ω_s) gives the rated flux. Synchronous speed is multiplied with rated flux to give the required voltage V_{ref}. Using V_{ref} and w_s, five 72° degree displaced modulating signals are generated. This voltage signal is divided with output of quasi network to give normalized modulating signal. To ensure steady state operation, relation of $m = 1 - D_{max}$ between the peak of modulation signal (m) and D_{max} should be maintained. The normalized modulating signal is saturated to m (or) $1 - D$. Conventional Sine PWM is used for generation of switching pulses by comparing the modulating signal with carrier signal. In addition to this, boosting pulses are generated by comparison of carrier signal with constant boosting references of $(1 - D)$ and $(D - 1)$. Resultant pulses are generated by performing logical OR operation between boosting pulses and conventional sine – triangle comparison pulses. These pulses are given to five leg qZSI to achieve desired V_{dc} and ac output voltage.

ii) *DC Voltage Controller*

Capacitor voltage V_{c2} is sensed into the control system. Output voltage of the quasi network (V_{dc}) is estimated by using the steady state equations using V_{c2} and D. Error is generated by comparing Vdc with reference value and this error becomes input for PI controller block. The controller gives inductor current reference i_{L2}. This is fed to the PI control loop to give D.

IV. SIMULATION RESULTS FOR V/F CONTROL

By implementation of V/f control to qZSI powered five phase induction motor drive, the following points should be ensured:

a) Starting of Induction motor must not be subjected to huge torque transients
b) V/f control must be ensured during all transients
c) Motor must be subjected to load-side transients to ensure stability of drive
d) Control of output voltage of quasi network must be ensured
e) Boosting of input voltage to the required level must be achieved to utilize the advantage of using qZSI
f) Steady state relation of m = 1-D must be ensured during operation

Table -1 gives the parameters of the five-phase induction motor and Table -2 gives the parameters of qZSI.

Table - 1: Specifications of Five Phase Induction Motor

Parameter	Specification
Power (P)	3 kW
Supply Voltage (V_s)	230 V
Rated Speed (N_r)	970 RPM
Stator Resistance (R_s)	25.3 Ohm
Rotor Resistance (R_r)	15.5 Ohm
Stator Inductance (L_s)	103.1 mH
Rotor Inductance (L_r)	92.2 mH
Moment of Inertia (J_m)	0.021 Kg.m^2

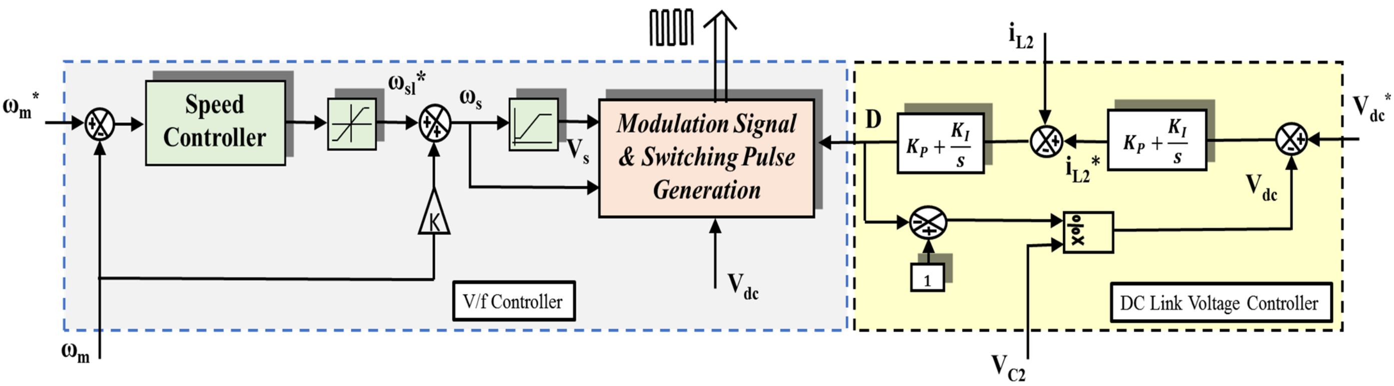


Fig. 3 Control Structure for implementation of V/f operation of Five Phase Induction Motor Drive fed with voltage controlled qZSI

Table -2: Specification of quasi Z Source Inverter

Parameter	**Specification**
Switching Frequency (f_s)	10 kHz
Quasi Inductor ($L_1 = L_2$)	1.2 mH
Quasi Capacitor ($C_1 = C_2$)	2 mF
Modulation Index (m)	0.80
D_{max}	0.20

The modelled system is tested by applying the speed reference and its response is observed. The disturbance is also applied from the output side by application of load torques in a stepped manner.

The sequence of the speed references and load torque application is as given below:

a) At 0 sec, the speed reference is set to 154 rad/sec.
b) At 2 sec, load demand is changed from 0 to -2 Nm.
c) At 4 sec, the speed reference is changed to 235 rad/sec.
d) At 6 sec, the load demand is changed from -2 to 2 Nm.

Fig. 4 shows the mechanical speed and electromagnetic torque response of the system for given speed references and load torque demands.

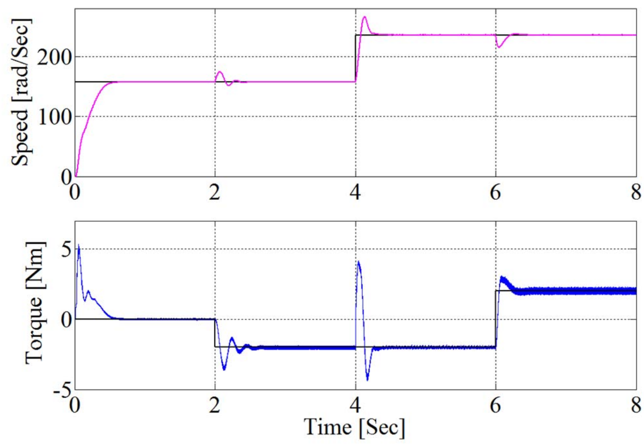


Fig. 4 Mechanical Speed and electromagnetic torque response of the five phase induction motor

At starting, the machine steadily rises to approach the required steady state speed. Once the motor reaches its steady state speed, the torque developed by the motor is reduced as there is no more requirement of acceleration of the motor. The modulating signal shown in Fig. 5 varies accordingly to keep the ratio Volt/Hertz constant. It can also be seen that the modulation signal has a low frequency at the starting with corresponding magnitude keeping V/f constant as demonstrated in Fig. 5(b).

The modulation signal should never exceed m (or) 1-D_{max}. In the control algorithm D_{max} is ensured to be 0.2, which means the peak of modulation signal should not be above 0.8 which can be observed in Fig. 5.

At 2 sec, the load demand is changed to – 2 Nm. For a drive operating in stable region, there should be a decrease in speed when positive load torque is applied to the system and the speed should increase when load is reduced. This behavior can be clearly observed in the response shown. After the speed increases momentarily, the control algorithm comes into action to restore the speed back to the reference value.

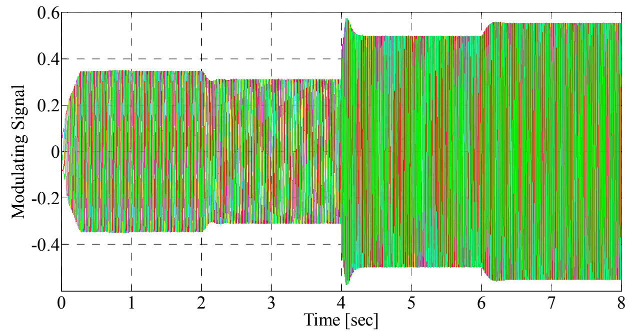


Fig. 5(a) Modulating Signal of the five phases ensuring V/f control is achieved during all operating modes

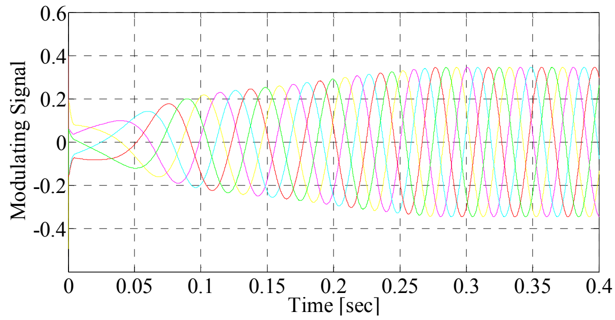


Fig. 5(b) During starting, frequency and magnitude of the modulating signal increases steadily

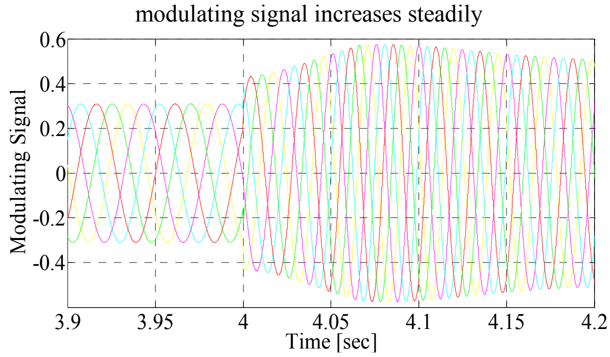


Fig. 5(c) When the speed reference is increased, frequency and magnitude of modulating signal increases steadily

Fig. 5 Variation of modulation signal magnitude and frequency during Volt/Hertz control.

At t = 4 sec, the speed reference is increased to 235 rad/sec from 134 rad/sec. To ensure fastest possible acceleration of the motor to the required speed, maximum torque should be applied. Once the speed exceeds the required speed, the torque becomes negative and the speed settles to the new reference value. Fig. 4 shows that control can meet

the load torque demand without any decrease in the steady state speed of the motor drive. Fig. 5(b) shows that during speed transient, the modulating signal increases its magnitude and frequency steadily to ensure minimization of transients.
At 6 sec, the load demand increases to 2 Nm. For stable region operation, the speed should decrease for an increase in load torque. The speed decreases momentarily and then control algorithm brings it back to the desired speed. Proper tuning of controllers ensures that transients are minimized, and fast settling of the drive response is achieved.

Output current of phase A of five phase induction motor is shown in Fig. 7(a). As already discussed, torque reference is changed at t = 2 sec. It can be observed as increase in the phase current magnitude. It is shown in Fig. 7(b). When speed reference is changed, the torque first increases then decreases which is reflected in the current waveform shown in Fig. 7(c).
Fig. 7(a) shows the boosting of the input voltage in qZSI. The input voltage is 300 V and dc bus input voltage for the inverter must be 350 Volts. Output of the quasi network forms the dc bus voltage of the five-phase inverter. By application of the shoot through mode, input voltage applied is boosted. Also, the dc bus voltage obtained is maintained equal during the entire operation.

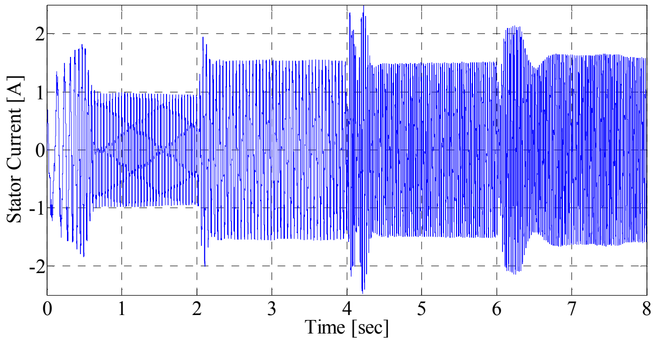


Fig. 6 Phase current of five phase induction motor

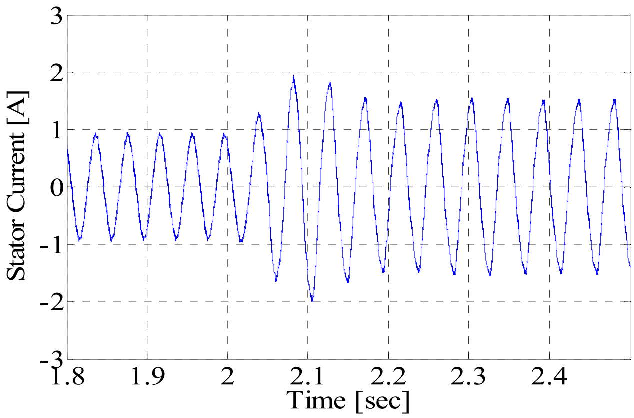


Fig. 6(b) Stator current during load torque change from 0 to -2 Nm

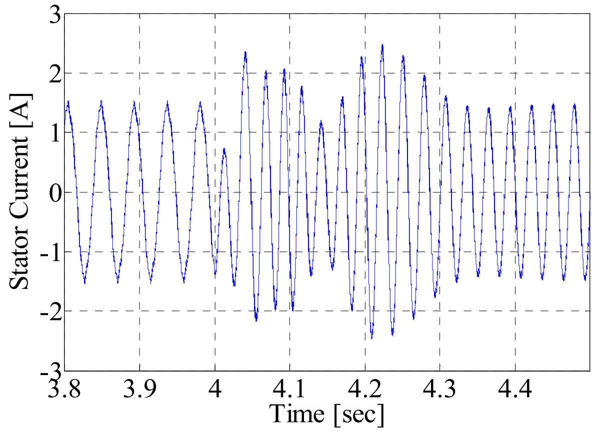


Fig. 6(c) When the speed reference is increased, frequency and magnitude of modulating signal increases steadily

As it can be observed in Fig. 7(a), the dc bus voltage remains constant during speed and load torque transients. Fig. 7(b) shows the inverter output phase voltage measured by connecting high impedance in star at the input of the motor terminal. The voltage measured between one point of high impedance and its star point will give the phase voltage of the motor.

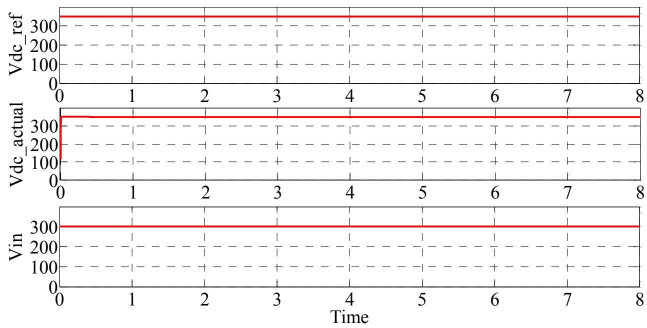


Fig. 7(a) DC bus voltage tracking

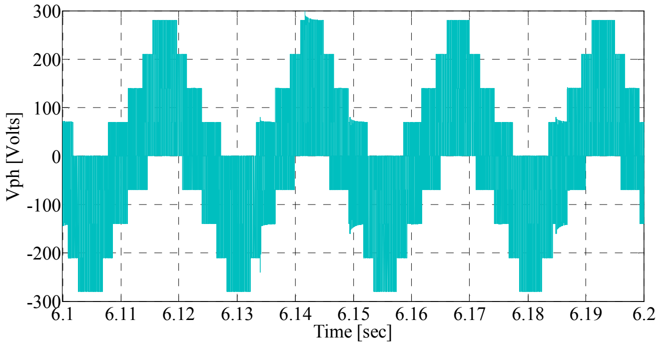


Fig. 7(b) Inverter output phase voltage

V. CONCLUSION

Five phase induction motor powered with five phase qZSI is presented in this article. Closed loop voltage control of qZSI is achieved by cascaded PI controllers. Boosting of input voltage is achieved by implementation of shoot through mode of qZSI. Voltage control of the motor is achieved by modulating the dc link voltage of quasi network and modulation index of the modulating signal. To achieve V/f operation of Five Phase Induction motor, mechanical speed is sensed and fed as input to the control algorithm. The system is tuned for voltage control of quasi network and tracking of mechanical speed of the motor when subjected to load perturbations. Performance optimization is ensured by considering the constraints of circuit relations during control algorithm implementation.

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