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Design of Active PWM Control Driver Circuit for Torquer System Using CCII

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ABSTRACT This research examines a torquer system for satellite attitude control which requires low energy, or average power, to control its moment. The magnetic torquer consists of an LR component, source and switching pulse. A mathematical model and design equations are presented for the magnetic torquer. A technique of using torquer system to do 3-axis spacecraft attitude control has been presented. The main goal of this system is to attain specific current control in the torquer system by means of CCII action. CCII is used since the full operation is performed in high frequency system. The closed loop control action of the controller, the triangular wave generator, CCII and torquer system are specific parameters used in this research. This scheme's performance has been considered via analysis and simulation model. The resulting closed-loop systems are robust with respect to parametric modeling ambiguity. The result attained by OrCAD PSPICE, belonging to Cadence design systems with respect to desired amount of current value proves the efficiency of the proposed research method.

INDEX TERMS Controller, CCII, triangular wave generator, torquer system.

I. INTRODUCTION

A satellite is exposed to slight but consistent disruption torques and forces. The key sub-system in satellite progression is the attitude control system. The attitude control system supplies are decided by the torquer system. A reaction wheel is basically a motor driven flywheel [1], which is a vital element used to control satellite attitude. Through applying appropriate control torque to the motor shaft, the wheel reaction momentum helps modify the satellite axial position precisely [2]. Surrounded by the prevailing motors, Permanent Magnet Synchronous Motor (PMSM) [3] is possibly the utmost suitable actuator in this application owed to its countless advantages, such as high-power density, low weight and small volume, high efficiency, high torque creating capability, high acceleration rate, etc. In particular, the Interior PMSM (IPMSM) possesses superior performance to those of surface-mounted PMSM (SPMSM). Moreover, the disk-type motor structure [4] and the amended bearing and wheel structures might further increase the whole reaction wheel efficiency and life [5]. On the other hand, in [6] the controls have been considered for attaining integrated power and single-axis satellite attitude control using two flywheels. The traditional feedback control methods make it challenging to attain the anticipated current and torque control necessities for a PMSM driven plant. To expand this, the humble robust

current and torque controls for a PMSM driven reaction wheel are inspected [7]. In the robust attitude control strategy, disturbance and uncertainties will not be excluded, and robustness to them is accomplished with standard attitude control performance. In contrast, the alternate approach to realize attitude control with noble accuracy is to cut off disturbance/uncertainties [8]. For this type of attitude, the magnitude or its upper bound of disturbance torque and uncertainties will be assessed, and then a controller will be designed to compensate for it. To attain this goal, adaptive control technique is one highly pragmatic approach [9]. In [10], an adaptive estimation law was first intended to evaluate the parameters of uncertain inertia. By using the estimated information, a nonlinear controller was suggested for attitude tracking operation. In [11], Chebyshev neural network was adopted to approximate the uncertain dynamics

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presented by disturbance and uncertain parameters. Using the estimated value, a terminal sliding mode attitude controller was suggested. An alternative solution to achieve disturbance uncertainties' rejection control is observer-based control design. In this approach, an observer is first designed to estimate disturbance/uncertainties, and the controller is developed based on the observed value. Presently, there are a number of surveys on designing observers to estimate disturbances [12].

More precisely, when inspecting disturbance as an unknown input, relating the theoretical framework of Unknown-Input-Observer (UIO) [13] is becoming an active way to estimate disturbances. For linear/nonlinear systems, the problem of high-performance control design by using UIO to estimate system uncertainties and disturbances has been broadly explored in [14]. A PD-type control approach was established for rigid satellites to accomplish attitude tracking maneuver. It was able to achieve a high-accuracy pointing control performance in face of disturbance torque, uncertain inertia, and even actuator dynamics.

Those uncertain dynamics can be recompensed with the application of this approach. Disturbance and uncertain inertia rejection control was achieved and this was owing to the incorporated observer-based estimation law, which was designed to estimate the uncertain dynamics with finite-time convergence of estimation error guaranteed. As a result, to be asymptotically stable, the closed-loop attitude tracking system was guaranteed. The structure of the proposed PD-type controller was quite simpler. Furthermore, the implementation of this approach was user/designer friendly, independent of actuator dynamics, and practically appealing. It did not include a time-consuming design procedure, and demanded less onboard computation. It should be noted that, the desired attitude trajectories were tracked asymptotically. In some of future work, one could extend the result to a finite-time control scheme. The planned attitude tracking maneuver can be accomplished as soon as possible with such scheme [15]. Satellite attitude can be controlled by several actuation methods, including thrusters, reaction wheels, magnetic torque rods, or a combination of above. Electromagnetic actuator is a particularly effective and reliable one. It interacts with the earth's own magnetic field in order to generate a control torque acting on spacecraft [16]. CCIIs are Current-Mode (CM) basic blocks [17] utilized in different applications, both in linear and nonlinear contexts. They could excellently substitute traditional Operational Amplifiers (OAs) in some applications. An oscillating circuit suitable for the read-out of resistive sensors and using a DC voltage signal for the sensor excitation and a suitable second-generation current conveyor (CCII) as active block has been developed in [18]. The use of CCII allows overcoming the traditional limitation of a constant gain-bandwidth product, typical of OAs, and offers all the current-mode benefits in low-voltage, low-power (LP) integrated architecture design [19]. A well-known current-mode circuit is the second-generation current conveyor (CCII). Current conveyors (CCs), are broadly used by analog designers specifically as basic building blocks for controller [20]. However, many applications require filter tuning. In particular, sophisticated techniques of signal processing demand the ability to adapt the filter characteristics dynamically. In such cases, it is desirable to vary the filter coefficients electronically [21]. Operational Transconductance Amplifiers (OTAs) can be used to perform the tuning but they suffer from restricted output voltage swing and temperature sensitivity.

A simple Pulse Width Modulator using relaxation oscillator cooperating with CCII has been recommended. It is simpler than PWM IC. It could yield the accurate PWM signal with widely operating carrier frequency. In addition, the proposed scheme can be also realized in IC form. Both the simulation and experimental results reasonably confirm capability and precision of generated PWM signal [22]. PWMs can process large signals with high efficacy and low sensitivity to noise. The PWM feedback systems belong to the field of power electronics having mixed features of continuity and jumps. Slightly unique and inherent nonlinear and discontinuous characteristics make the design task of power electronics field much more difficult [23]. Thus, it is not only practical but also enough of a challenge to design the optimal controllers of the PWM feedback systems with bilinear plants.

In order to design the subsystem of satellite attitude determination and control system, in most cases, three reaction wheels are deployed in line with the three main axes of the satellite. Each of this actuator has an electric motor and a heavy disk. By applying current to the electric motor, torque is generated, which changes the speed of the angles of the motor axis. Changing the speed of the reaction wheel by applying the necessary control algorithm to the motors bases the motor to reach the mandatory speed from zero speed. After generating the necessary torque, the motor shuts off again. This change in speed causes the required tower radiation to be created to attain the desired state of the satellite [6]–[8]. In general, control of a satellite that turns out to be under actuated as a result of onboard failures has been a recurrent theme [25]. Techniques for controlling spacecraft with fewer actuators than degrees of freedom are ever more in demand due to the increased number of minor satellite takeoffs [26]. Magnetic torquers have been broadly examined for momentum management of spacecraft with momentum wheels and for nutation damping of spin satellites, momentum-biased satellites, and dual-spin satellites [27].

Since the torque system in satellite is the sensitive parameter which affects the target mission of any satellite, proper control mechanisms should be adopted for attaining smooth functioning of the satellite system. The current research work focuses on achieving appropriate current control in the torque system action of a satellite by incorporating CCII action. The major contribution of the proposed work is to design a PWM control driver circuit for satellite's torquer system. The proposed driver circuit will control the current in the torquer system which will again change the satellite orientation as per requirement. The observations of based on op-amp PWM are used for operations of low frequency due to finite loop bandwidth and limited slew rate. So capable high speed switching controllers with high frequency active block is needed.

In this article, the second-Generation current conveyor is chosen as an Active block to design the control circuit. Due to attribute, they provide higher signal processing bandwidth with good linearity and larger dynamic range than operational amplifiers (op-amps) based ones. To make the torque system trigger, suitable gate pulse should be fed to the switch which is generated by the combined act of triangular wave generator and controller. When this switching pulse is given to the torque system, the duty cycle changes which in turn changes the current value. The other contribution of proposed research in the simulation and the real time implementation design using driver circuit using AD844 IC's and the experimental implementation of the design. The simulation results are synchronized with the real time results to substantiate the analysis approach

The organization of the paper is as follows: the next section presents Overview of the Second-Generation Current Conveyor, Torquer System of satellite and the Basic Control Arrangement. The architecture of the PWM control and Proposed Closed loop control driver circuit also discussed in that section. The third section presents the Simulations and Experimental validation of Results. A comparison of the case study results is also presented to evince its significance. and finally, the conclusions are presented in the last section.

II. OVERVIEW OF THE CCII, TORQUER AND THE CONTROL ARRANGEMENT CCII

A. SECOND GENERATION CURRENT CONVEYOR

A current conveyor is an intellection for a three-terminal device. When designed with other circuit components, actual current conveyors could accomplish many analog signal processing functions, in a fashion analogous to the way op-amps and the ideal perception of the op-amp are used. The current conveyor circuit was presented by Sedra and Smith in 1968. While compared to the OAs, CCII possess high gain-bandwidth product and the power consumption is found to be lower. Basic representation of the CCII block is mentioned in Figure-1:

$$\begin{bmatrix} i_y \\ v_x \\ i_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & \pm 1 & 0 \end{bmatrix} \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix} \tag{1}$$

B. TORQUER SYSTEM AND ITS MODELING

A magnetic torquer system is a current carrying coil, or a permanent magnet, which produces a magnetic field. The interaction of the magnetic field produced by the magnetic torquer with the earth's magnetic field causes a torque on the torque. It gets transmitted to an earth orbiting satellite if the magnetic torquer is fixed to the assembly of the satellite. By governing the resultant magnetic moment on a system of magnetic torquers while measuring the magnitude and direction of the earth's magnetic field, it is possible to control the resultant torque on a satellite for attitude control or desaturation of momentum storage devices used for satellite attitude control purpose.

FIGURE 1. Block diagram of CCII.

TABLE 1. Magnetic torquer parameters.

Parameter	Value
Magnetic dipole moment, Am^2	0.15
Coil Resistance, Ohm	38
Coil Inductance, mH	18
Number of turns	370

In a satellite system, the appropriate torque control is determined with the support of the control system. Torque gets generated by means of passing electric current through torquer. Since the microcontroller generates voltage signal and hence it is obligatory to examine the relation between the voltage applied to the torque system and the current value generated from it. The basic torquer circuit includes an inductor in series with resistance circuit (L-R) and a voltage source. The electric current response to the applied voltage is specified by means of a transfer function mentioned in equation (2) & (3) as:

$$I(s) = \frac{1}{R + LS} Vin(s) \tag{2}$$

$$I(s) = \frac{1}{38 + 0.018S} Vin(s) \tag{3}$$

The basic equivalent circuit of torque system is mentioned as follows:

Initially, the current flowing through the LR path will be zero. When a MOSFET switch is connected across V_{in} source, pulse from the switch triggers the circuit and the current I_0 flows across the circuit. The resistor value is 40 ohms and the inductor is 18 mH. The maximum value of current value is 1 A across the circuit. In accordance with the corresponding current value requirement, the duty cycle of the pulse could be modified. The duty cycle (D) is the ratio of ON time to the total time period as mentioned in equation (4).

$$\mathbf{D = T_{ON}/T} \tag{4}$$

The exact requirement of current value is 1 A for torque action. In order to attain the specified current value, the proposed approach consists of a controller system, which is the proportional controller. The chief aim of the current research is to design a control circuit for the torque action. The design

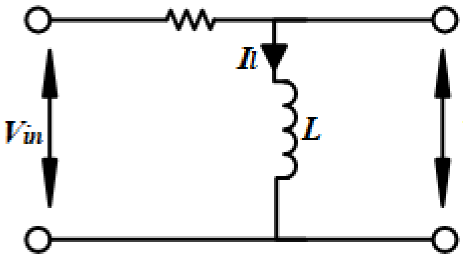

FIGURE 2. Equivalent circuit of torquer system.

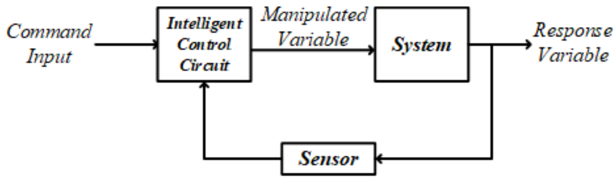

FIGURE 3. General block diagram of Control system.

parameters and working of the controller circuit is described in the following section as follows.

C. GENERALIZED CONTROL BLOCK DIAGRAM

In this current research, a driving circuit is designed, developed and controlled with minimum resources and affordable cost value. The PWM driving circuit drives the torquer current system. In the controller circuit, the closed loop control mode activates and driver circuit will be reliant and precise due to the feedback action and this could sense the output current value. The duty cycle is modified in accordance to perform the control action. For the purpose of establishing the driver circuit, the closed loop control is directed.

The basic building block of the control system is described in Figure 3. Here, the intelligent control circuit compares both the input command and the feedback response value. The controlled form of output will be fed to the PWM modulator which in turn yields modulated form of output. This modulated output will force the system to generate the necessary current value. This process is trailed in this current research to control the current value in the torque system. The PWM control architecture is displayed in Figure 4.

The relationship between output current and input reference voltage is derived in Laplace domain, which is a 1^{st} order system model having a pole in left hand side making the system stable.

$$E(s) = V_{ref}(s) - V_f(s) \tag{5}$$

$$V_{m(in)}(s) = k_1 k_3 DE(s) \tag{6}$$

$$I_0(s) = V_{m(in)}(s)\frac{1}{[R + sL]} \tag{7}$$

$$I_0(s)[R + sL] = k_1 k_3 DV_{ref}(s) - k_1 k_2 k_3 DI_0(s) \tag{8}$$

$$\frac{I_0(s)}{V_{ref}(s)} = \frac{k_1 k_3 D}{sL + (R + k_1 k_2 k_3 D)} \tag{9}$$

D. CONTROL DRIVER CIRCUIT DESIGN

The closed-loop control driver circuit configuration is presented in Figure 5. The CCII-based PWM control driver

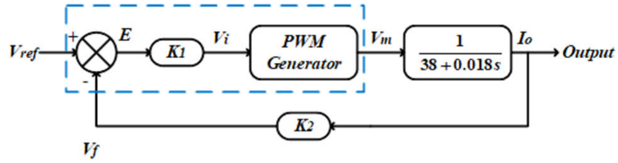

FIGURE 4. PWM control architecture.

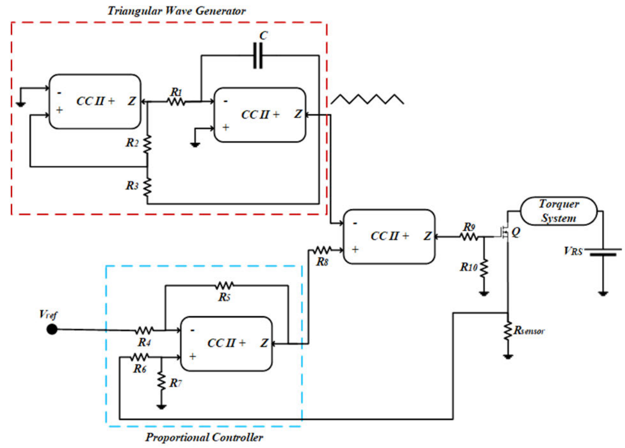

FIGURE 5. Proposed closed loop control driver circuit.

circuit is mainly proposed to control the current, I_0 in the torque system. The duty cycle of the PWM will be modified by the input which in turn maintains the required amount of current in the torquer system. The required amount of current value will be identified from the processor as a reference voltage during every cycle of the processor action. In the given circuit, the actual current is compared with the required current and controller will take action on the error information to make it zero by modulating the duty cycle. The command reference and present current information will go to the forward path of the control circuit and based on this two information, required current will flow in torquer system. Again, the current through torquer will also flow in the sense resistor as shown in the schematic diagram. This current information is again fed back to the controller as a negative feedback to ensure the required current in the Torquer System.

Here, in the closed loop control configuration, triangular wave generator [28] block is present and the proportional controller block produces the error signal.

The triangular wave and the error signal is fed as input to the CCII block which generates the PWM pulse output. This PWM output is the input pulse to the MOSFET switch which is connected to the torquer circuit. Once the pulse given to MOSFET triggers, the current flows in the torque system and it acts. In this proposed approach, the current requirement is 1 A. The input voltage given to the controller varies from 0 to 3.3 V. The main function of the torque system is for attitude control in a satellite where it mainly controls the orientation of the satellite. Once any external torque disturbs the satellite, the torquer system acts which cancels the external torque

TABLE 2. Values of parameters in the proposed circuit.

Parameter	Value
R1	7.8K
R2	70K
R3	25K
R4	1.5K
R5	5.6K
R6	1.5K
R7	5.6K
R8	100ohms
R9	1K
R10	20K
C	350uF
K1	3.733
K2	0.2
K3	12.2

action such that the actual focus of the satellite will be approximately saved. The satellite focuses on a particular area on the earth. In case the outside torque disturbs the satellite system, the precise destination of the point might be varied. Hence, the chief aim of this proposed research is to design the control circuit feature for the torquer action in a satellite. There is a minimum time period in which the torquer system acts when some outside torque arrives, otherwise the satellite orientation will be disturbed and the oscillation occurs. For example, at the point t = 0, some external torque occurs, the torquer system should act as soon as possible. If the time period of torquer system exceeds to t = 1, then the overall system gets diverted and distortion occurs. Therefore, there exist certain limitations of the rise time (T_r) and the settling time (T_s) of the satellite. The rise time and the settling time should be as low as possible in order to make the satellite propulsion smooth. Consequently, when the rise time is as low, the bandwidth value gets increased. Thus, the operation must be taken place in a high frequency system. This is the reason of adopting CCII in this research. The input fed to the microprocessor is 0-3.3V and some digital to analog converters are deployed in the microprocessor system. The reference voltage is 0-3.3V and the corresponding output current requirement is 1A. The torquer system parameter is given as 1/(38+0.018s). Considering all parameter, the proposed model in Laplace Domain is given by equation (10),

$$\frac{I_0(s)}{V_{ref}(s)} = \frac{2528}{s + 2616} \tag{10}$$

The current value, I_0 flows across this load parameter and it gets multiplied with the constant factor k2 and the V_f will be attained. Here, the I_0 current flows across the 40V supply voltage and reaches the resistance. Initially, when the current is zero, the value of V_f will be zero and when the current value is 1, the reference voltage will be 0.2V. When the reference voltage V_f fed to the CCII is 3.3V, it acts as a differential amplifier. So, the difference will be calculated and the error signal (e) will be determined. The error value will be multiplied by the constant k1. The triangular wave generator will produce the triangular wave [28] and the triangular wave value could be modified by changing the value of the capacitor. So, according to the requirement, the capacitor value can be varied, and hence the frequency gets changed. When high frequency is required, the capacitance value should be of minimum.

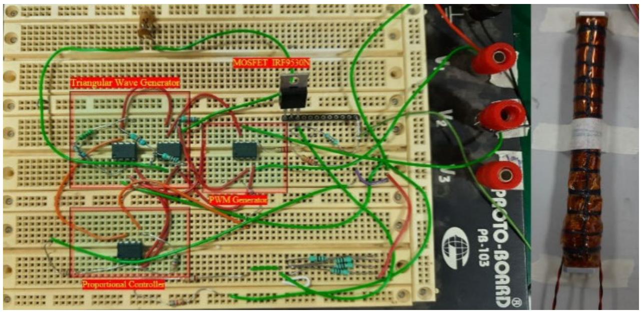

FIGURE 6. Experimental setup.

In order to make the torquer system function, the pulse should be given to the MOSFET switch which requires PWM pulse. The PWM pulse will be obtained from CCII output. The input to the CCII will be the triangular wave from the triangular wave generator and the error signal from the proportional controller. In accordance with the error value, duty cycle changes. When the error value is 1, the duty cycle will be 80%, when the error value is 2, the duty cycle will be 85%, likewise. When the duty cycle varies, obviously the current value also changes.

In the proposed approach for the control of torquer-control mode, the current value I_0 will be multiplied by the sensor resistance k2 and hence the voltage will be attained. This generated voltage will be compared with the reference voltage and the error occurs. That error will be multiplied by the constant k1 and this constant k1 will change the duty cycle. When the duty cycle changes, finally the current value will be changed and so the desirable current value will be attained.

III. SIMULATION AND EXPERIMENTAL RESULTS

OrCAD PSPICE belonging to Cadence design systems is widely used for electronic circuit simulation and verification. The controller is experimentally implemented using the commercially available IC AD844 of Analog Devices which is equivalent of second-generation current conveyor.

The complete hardware setup for the proposed approach is presented in Fig. 6. Here, the breadboard includes the triangular wave generator composing of two CCII actions. Then the proportional controller which produces the error signal. The PWM pulse from the CCII output is fed to the MOSFET switch, which triggers the torque system. The voltage source is fed from the V_1 and V_2 supply. Proper ground connections are maintained.

The step response is shown in Fig.7. The control action is dependent on the modulation factor of the duty cycle; change in duty cycle will be reflected in the output current.

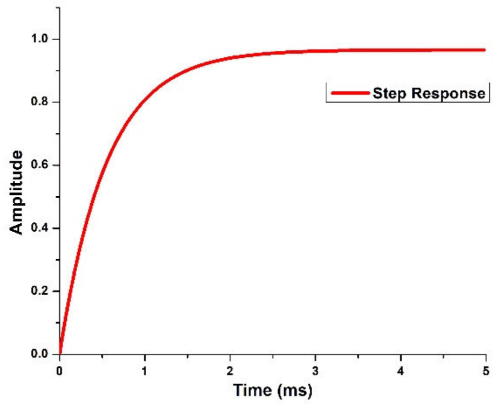

FIGURE 7. Step response.

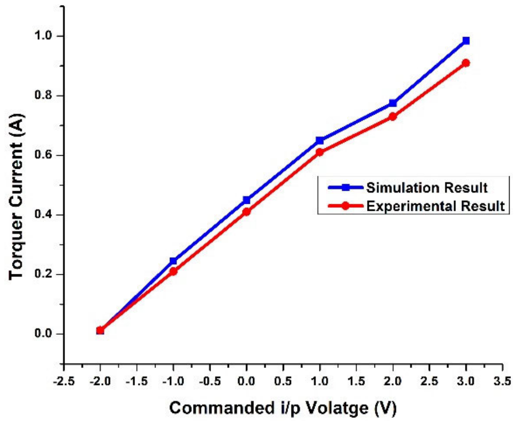

FIGURE 8. Torquer current vs input voltage.

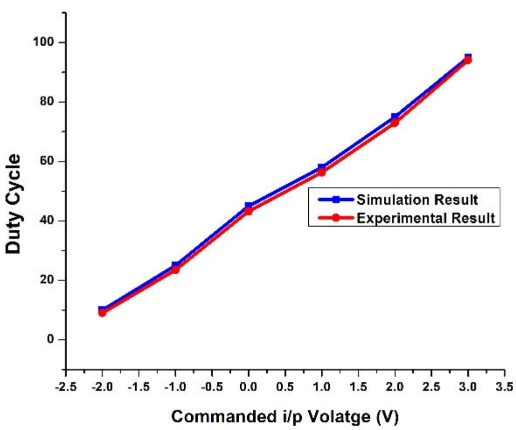

FIGURE 9. Duty cycle vs (reference input voltage).

In Fig.8, the linear behavior of the current due to duty cycle is presented. Fig. 8 shows that with respect to the desirable current requirement, the duty cycle could be modified. The Fig.9 shows the linear nature of the Torquer current and reference voltage. It is clear from the graph that when the reference voltage varies, the duty cycle values changes and when the duty cycle changes, the current flowing across the circuit changes.

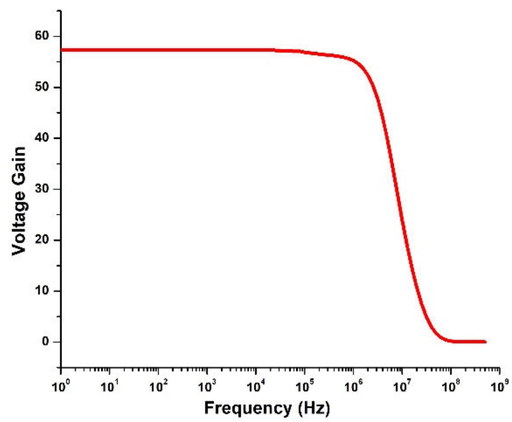

FIGURE 10. Gain vs frequency.

Here, in all the output result parameters, they are predicted in terms of simulation results and hardware experimental results which prove the theoretical and practical dynamics simultaneously.

Here, the bandwidth can be extended up to 10MHz. The voltage source of the torquer system varies in accordance with the weightage of satellite. If the satellite requires more torque, then the current requirement is also more since torque is directly proportional to current. The voltage source differs in each satellite depending upon the satellite design. In some satellites, the source might be 40V, 25V or even 15V. The similar circuit topology used in this proposed approach is applicable for any 40V, 25V or 15V satellite system. The input voltage requirement in controller is the same 0 to 3.3V for any of the above-mentioned satellite parameters. But the current value varies accordingly. The gain vs frequency plot shown in Fig.10 dictates the proficiency of controller to work with high frequency system. In PWM control circuit, higher switching frequency will always produce the ripple at output level. This is the major reason where the researchers set the switching frequency up to 1 MHz. As per the frequency plot, the driver circuit is very much capable to work at frequency level up to 10 MHz.

The triangular wave output shown in Fig.10 is generated by two CCII [28]. The frequency of wave tuned to 40 KHz is continuously fed to PWM. The time period of wave is linearly dependent on value of capacitor C.

Here, the proposed control driver circuit is designed for 40 V (1 A), 25 V (650 mA) and 15 V (400mA) operation. The same circuit can be used for all three operations as per requirement and duty cycle can be achieved from 5% to 95% with respect to reference commanded voltage. The Fig. 12, 13 and 14 shows the Torquer current waveform with respect to time for different duty cycle values. Fig.12 denotes the change in current with respect to various duty cycle values in 40 V satellite systems. For 80% duty cycle, the current value is 1 A and for a minimum of 20% duty cycle, the current value is 0.2 A. Fig.13 denotes the change in current with respect to various duty cycle values in 25 V satellite system. For 95% duty cycle, the current value is 650 mA and for a

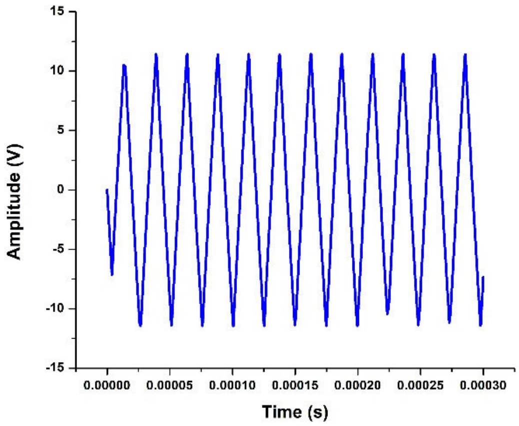

FIGURE 11. Triangular wave o/p.

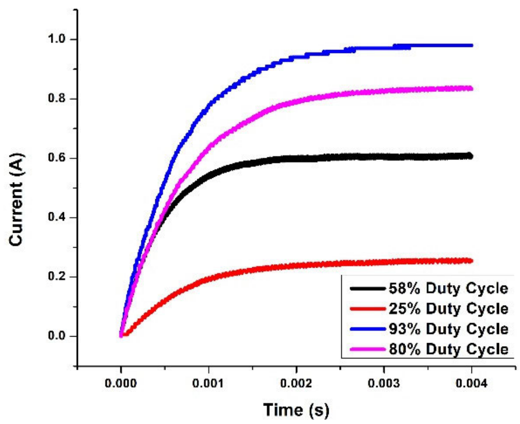

FIGURE 12. Torquer current for 40_Volt operation.

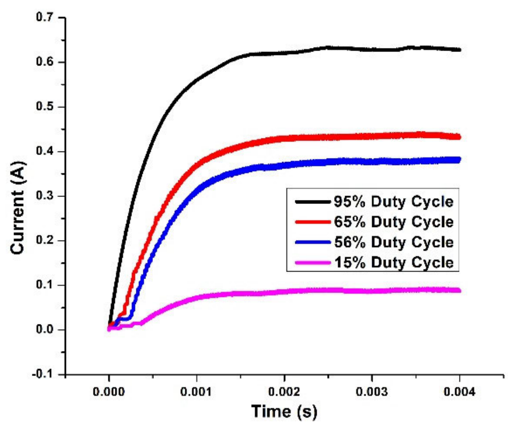

FIGURE 13. Torquer current for 25_Volt operation.

minimum of 15% duty cycle, the current value is 0.05 A. Fig.14 denotes the change in current with respect to various duty cycle values in 15 V satellite system. For 95% duty cycle, the current value is 0.38 A and for a minimum of 15% duty cycle, the current value is 0.005 A. The Fig.15 specifies the overall current requirement graph, which is attained by the action of reference voltage. It is clear from the graph that reference voltage input of 3.3 V changes the duty cycle and the current value constraint of 1 A is achieved.

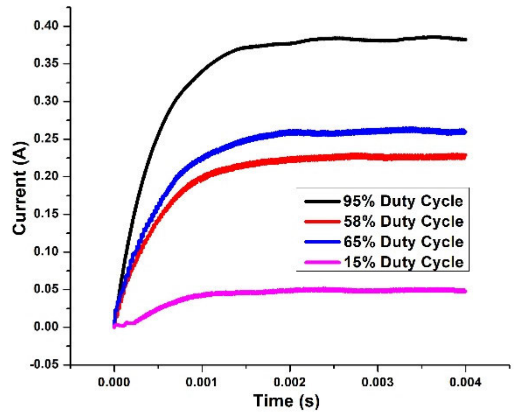

FIGURE 14. Torquer current for 15_Volt operation.

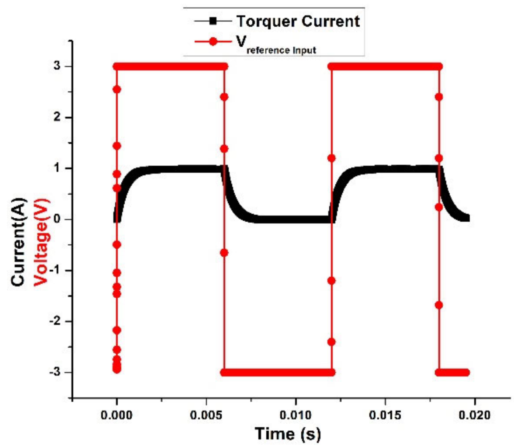

FIGURE 15. Torquer current versus voltage reference.

The comparison between the proposed PWM driver circuit and other existing literature is given in Table 3. In previous researches majority of the work is done as open-ended configuration only means the performance of the circuits are evaluated without a real time system. Proposed PWM driver circuit designed and implemented with the real time system which is satellite's torquer system. As per the available literature CCII based PWM driver circuit for satellite's torquer system has not been reported till now, so the comparison is done in terms of number of active or passive component required to design a PWM control circuit in open ended configuration as shown in Table 3. Kim *et al.* [29], Ranjan *et al.* [32] have used more active components then our proposed design. The authors Chien [30], Ranjan and Paul [38], Silapan and Siripruchyanun [36], and Silapan and Siripruchyanun [33] have used hybrid block which is again made by using original current mode device such as current conveyors and OTA. Whereas one DVCC corresponds to 3 CCII and one MO-CCCDTA is made from 2 CCII and 3 OTAs.

IV. CONCLUSION

The current research approach focused on desirable current requirement in the torquer system of a satellite with the support of CCII action. The input of the CCII was fed from

TABLE 3. Comparative table specifying performance parameters considered in previous researches.

References	No. of active components	No. of passive components	Carrier signal Generator Requirement	Electronic Tunability	Highest frequency of operation
[29]	1 OTA, 1inverter and 1 MOS switch	1 capacitor (Gnd), 1 resistor (Gnd)	No	Yes	NA
	4 OTA,1 inverter	1capacitor (Gnd),1 resistor (Gnd)	No	Yes	NA
[30]	3 DVCC	1 capacitor (Gnd), 3 resistors (Gnd)	Yes	Yes	Hundreds of KHz
[31]	3 OTA	1 capacitor (Gnd), 2 resistors (Gnd)	No	Yes	Tens of KHz
[32]	4 OTA	1 capacitor (Gnd)	No	Yes	Few of KHz
[33]	2 MO- CCCDTA	1 capacitor (Gnd)	Yes	Yes	Hundreds of KHz
[34]	3 op-amp	3 capacitors, 7 resistors	No	No	Hundreds of KHz
[35]	1 CC-II, 2 op-amp	2 capacitor (Gnd), 3 resistors (Gnd)	Yes	No	Few of KHz
[36]	1 MO- CCCDTA,	1 capacitor (Gnd), 1 resistor (Gnd)	Yes	Yes	Few MHz
[37]	1 OTRA	1 capacitor (floating), 3 resistors (floating)	Yes	No	Few MHz
[38]	1 modified MO-CCCDTA	1 capacitor (Gnd)	Yes	Yes	Few MHz
Proposed Design	**3 CCII**	1 capacitor (floating), 3 resistors (floating)	No	Yes	Few MHz

the triangular wave generator and the proportional controller. For the generation of torques for attitude control of earth-orbiting satellites, it is concluded that control of the current in the torquer is controlled by the duty cycle of the switching pulse and the duty cycle is controlled by the reference voltage of CCII. The maximum current requirement in this proposed research is 1 A. This particular circuit design is applicable for various voltage range satellites such as 40 V, 25 V and 15 V, only the corresponding current value changes. Table 3 presents the comparative analysis of building components required for PWM circuit application with previous researches done so far. Detection and diagnosis of fault is an essential research area which is mainly appropriate for the control design of the closed loop driver circuits. However, for practical implementation of driver circuits for torquer system in a satellite, redundant driver circuit is also provided for reliable operation. When the main driver circuit fails the standby or redundant driver circuit is automatically brought in to the action to continue the desired operation. However, investigation of the fault diagnosis is potential area for the future research.

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