Water Discharge Control in BLDC Motor Driven Pumps to Increase Drip Irrigation Accuracy

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Abstract— **Drip irrigation is the most energy and water-efficient irrigation. Multi-sector drip irrigation systems can irrigate different types of crops in several sectors. Changes in irrigation capacity due to changes in the active sector or disturbances in irrigation networks cause changes in pump head loss and result in changes in pump discharge. As a result, the water supply becomes unstable, and irrigation accuracy decreases. Therefore, it is necessary to control the discharge of the water pump so that even if the pump head changes, it still produces a stable water discharge. This study proposes a constant water discharge control for multi-sector drip irrigation water pumps so that the pump discharge follows the irrigation capacity. Pump discharge control uses the proportional integral and derivative (PID) method. The centrifugal water pump is driven by a Brushless DC (BLDC) motor. The test results show that the system can maintain the water flow rate constant even though the pump head loss experiences a significant change.**

Keywords— BLDC, Drip irrigation, PID, Water Pump

I. Introduction

Plant growth depends on the availability of water in the place of growth. Vegetables have shallow roots and need high nitrogen fertilizer [1]. Too much irrigation causes the nitrate in the soil to dissolve. Insufficient irrigation causes stunted plant growth. Therefore, irrigation plays a very important role in the agricultural process. Excessive or very less irrigation has an economic impact on agricultural products [2]. Precision irrigation is a modern concept that gives plants water according to plant needs, soil conditions, and environmental weather. This Irrigation method is one of the solutions to increase agricultural output because it is economical and appropriate for water and energy use. Behind the goodness of precision irrigation, there are several obstacles in design and management. In the design step, precise calculations are needed regarding water requirements, water network infrastructure, water sources, pump drive energy, and the ability of water pumps. During the operation phase, precise control regarding irrigation scheduling as needed. The most widely used precision irrigation types are sprinkler and drip irrigation [3]. Drip irrigation has the highest efficiency in water use [4-5]. In drip irrigation, water is given to plants through small droplets with a relatively long duration. So that percolation becomes very small, and the amount of water absorbed by the roots is more optimal [6].

A drip irrigation system requires a pressurized water source. Pressurized water generation is obtained through 2 methods: a system with pumping through overhead water tanks and a system with direct pumping [7]. In the overhead water tank method, water from the reservoir is pumped first to the overhead tank and then flowed to the irrigation pipeline [8]. In the direct pump method, water from the reservoir is pumped directly into the irrigation pipeline. Energy use in the direct pump method is more efficient than the pumping method through the overhead water tank. The amount of emitter debit affects the accuracy of irrigation because the volume of water given to plants depends on the amount of emitter debit and the duration of irrigation [9]. Multi-sector drip irrigation systems with different types of plants have different irrigation durations in each sector. The irrigation duration for different sectors causes the number of active sectors to change. If pump speed does not accompany the change in the number of active sectors, then the emitter discharge will be variable, and irrigation accuracy will be poor. Poor irrigation accuracy results in deficient plants or overwater, so productivity decreases. Therefore, it is necessary to control pump discharge based on the number of active emitters to achieve good irrigation accuracy.

Several researchers have carried out emitter discharge control in drip irrigation so that it is stable and uniform. A study has compared the energy efficiency of irrigation using an induction motor-driven centrifugal pump with speed regulation using a variable speed drive (VSD) [10]. Pump control using VSD is quite effective, but the control was done manually in that study. Research carried out irrigation management by scheduling pump activation arranged in parallel to produce a certain pressure [11-12]. Even though the research produced accurate irrigation, it required a lot of money. Some researchers control irrigation pressure through pump speed control based on the pressure of the irrigation network [13-16]. Some of these studies use complex methods that are not easy to implement using a standalone microcontroller.

The novelty in this paper is a constant water pump discharge control system for drip irrigation to increase irrigation accuracy with the PID method. This system controls the speed of the BLDC motor driving the pump to produce a constant water discharge. A constant water flow rate results in a more stable emitter discharge in the irrigation network, so the volume of water supplied to the plants is more accurate. A system prototype has been created to verify the proposed method.

This paper is structured as follows, materials and methods in section 2. Results and discussion are presented in Section 3. Finally, Section 4 concludes the paper.

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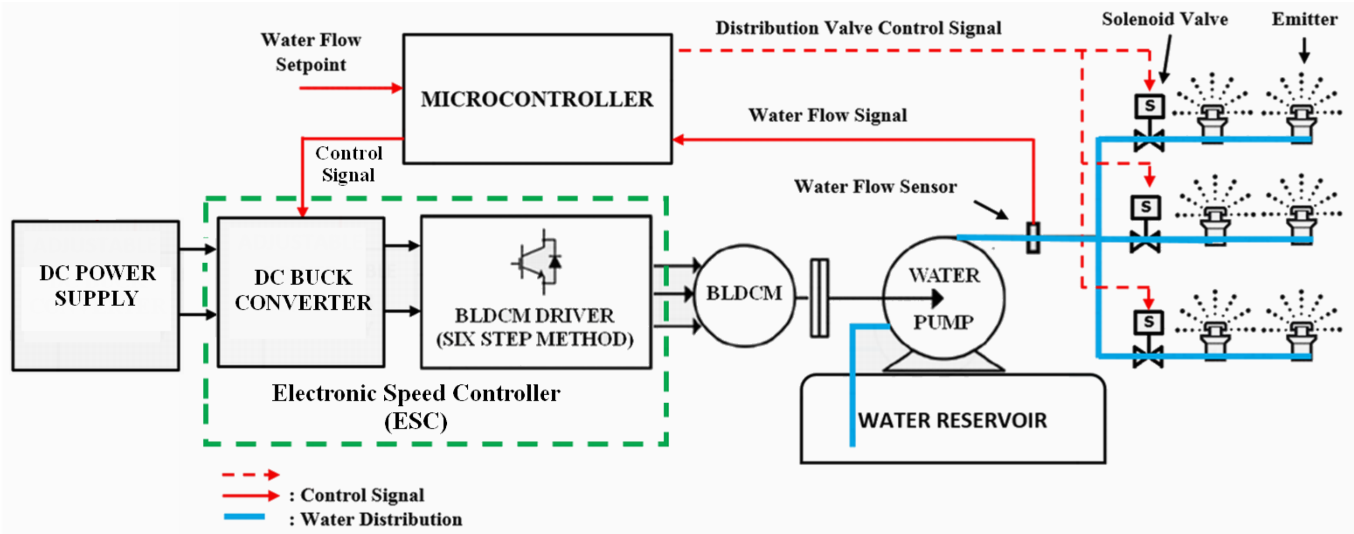


Fig. 1. Functional diagram of a water pump discharge control based on BLDC motor control

II. Material and Methods

The discharge of a water pump driven by a BLDC motor is controlled to produce capacity according to the number of active emitters. The water pump delivers water from the reservoir to the plants through a drip irrigation network. The functional diagram of this system is shown in Fig. 1. Drip irrigation networks have several emitters on each lateral pipe. Electronic valves activate water flow in an irrigation sector, where a sector consists of several lateral pipes. The microcontroller regulates the activation of the solenoid valve with a schedule and duration according to the type of plant. All lateral pipes are connected to the main pipe or manifold. The manifold is connected directly to the pump discharge, while the suction part of the pump is connected to the water reservoir. The water pump in this system is centrifugal type. The pump is driven by a BLDC motor on one shaft where the impeller rotational speed is the same as the motor shaft rotational speed. BLDC motors are driven by an inverter that converts DC voltage into 3-phase voltage.

The rotational speed of the impeller and the BLDC motor is proportional to the output discharge of the pump. The speed of the BLDC motor is regulated based on the water discharge from the water flow sensor mounted on the manifold pipe. The controller is an 8-bit microcontroller with the Integral Proportional (PI) method. The control signal from the controller is used to change the magnitude of the DC Link voltage on the electronic speed controller (ESC). The controller set point value corresponds to the total capacity of the active emitter discharge.

A. Drip Irrigation Network

The drip irrigation network in this study supplies water for 15 plants. The type of emitter used is spray with a discharge for each emitter of 30 l / h. The plant area is divided into three irrigation zones. The main network connects the pump output in each zone with three lateral pipes. A solenoid valve controls each lateral pipe. Each lateral pipe has five emitters. The three lateral pipes represent three irrigation zones. When all three zones are supplied together, the required flow rate is 450 l / h. A 300 l / h water supply is needed when only two zones are given. When only 1 zone is supplied, it only requires a debit of 150 l / h. A microcontroller regulates the activation of water delivery to each zone by activating the solenoid valve.

B. BLDC Motorized Water Pump

Centrifugal pump is a mechanism that can centrifugally compress water pressure into volute pumps with a pump impeller [17]. The centrifuge pump head's magnitude depends on the pump speed, defined as (1) [18].

$$H = \frac{V_p{}^2}{2g} \tag{1}$$

where H is the whole head (m), g is the acceleration of gravity (m/s^2), V_p is the speed of the water at the impeller (m/s). Equation (2) determines the water speed at the impeller.

$$V_p = \frac{N\ D}{299} \tag{2}$$

where N is the revolution of the impeller (RPM), D is the diameter of the impeller. Equation (3) formulates the relation between pump speed and discharge.

$$Q_p = 449 V_p A \tag{3}$$

where Qp is the water flux (m3/s), A is the water conductor area (m2). The power given by the pump to the fluid is called the water horsepower, formulated as (4).

$$W_{water\ horsepower} = \rho g H_p Q_p \tag{4}$$

where Water horsepower is the output power of the pump (watt), and ρ is the density of the fluid (kg/m3). The magnitude of the pump shaft power required to drive the impeller is called Brake horsepower (bhp), formulated as (5).

$$bhp = \omega_p T_p \tag{5}$$

where *bhp* is brake horsepower (watt), ω_p is the angular velocity of the pump shaft (rad/s) and T_p is shaft torque (Nm). The performance of the water pump is accomplished by contrasting the output power of the pump or the water horsepower to the input power of the pump or the brake horsepower.

BLDC motor consists of permanent magnet rotors and stator coils. The driver circuit is similar to the inverter on a 3-

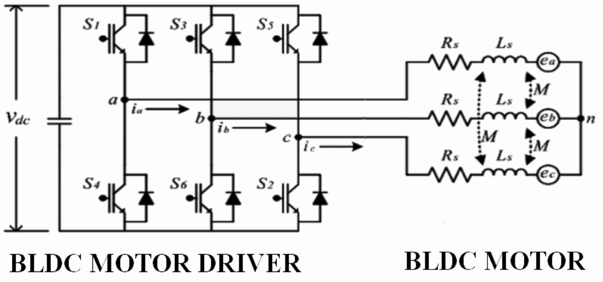


Fig. 2. Equivalent circuit of BLDC motor.

phase AC motor. The BLDC motor model and driver are shown in Fig. 2 [19]. This motor control system requires a feedback signal from the rotor position [20-21]. The position of the rotor can be determined based on the condition of the hall sensor mounted on the stator.

The magnitude of line to neutral voltage is:

$$V_a = Ri_a + L\frac{di_a}{dt} + e_a \quad (6)$$

$$V_b = Ri_b + L\frac{di_b}{dt} + e_b \quad (7)$$

$$V_c = Ri_c + L\frac{di_c}{dt} + e_c \quad (8)$$

where L and R are armature self-inductance (H) and armature resistance (Ω), respectively.

The back EMF voltage values are:

$$e_a = K_e f(\theta_e)\, \omega_r \quad (9)$$

$$e_b = K_e f(\theta_e - \tfrac{2\pi}{3})\, \omega_r \quad (10)$$

$$e_c = K_e f(\theta_e + \tfrac{2\pi}{3})\, \omega_r \quad (11)$$

Electromagnetic torque is obtained by [22]:

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_r} \quad (12)$$

Equivalent circuit of BLDC motor.

$$P_i = V_{DC} I_{DC} \quad (13)$$

$$P_o = T_e \omega_r \quad (14)$$

The input power is calculated by multiplying the voltage and the current of the power source used by the motor, expressed in (13). The output power Po results from the multiplication between the torque generated by the motor and the speed defined in (14) [8].

This system's type of water pump is centrifugal with a brushless DC drive motor. The pump characteristics are shown in Fig. 3. The water pump used in this study is DC50E-24150. The pump has a maximum head capability of 15 m when discharge is 0 l / m, and maximum discharge is 26 l/m when the pump head is 0 m.

This pressurized irrigation system requires a pump with a maximum discharge of 450 l/hour and a working point of the pump at a pressure range of 11 m. The pump impeller and the motor drive are connected in one shaft, so they have the same rotational speed..

The motor that drives the pump in this system is the BLDC motor. The motor has specifications of 1-ohm resistance, 0.6 H inductance, and a peak line-to-line voltage of 3.7V at 1000 rpm. The motor is supplied with a voltage of 24V through an electronic drive. The BLDC motor drive uses the Six Step method to regulate the current in the stator coil. This method requires stator position information. This information is obtained from the back emf signal from the stator coil. The motor's speed regulation is done by regulating the DC supply voltage at the motor drive.

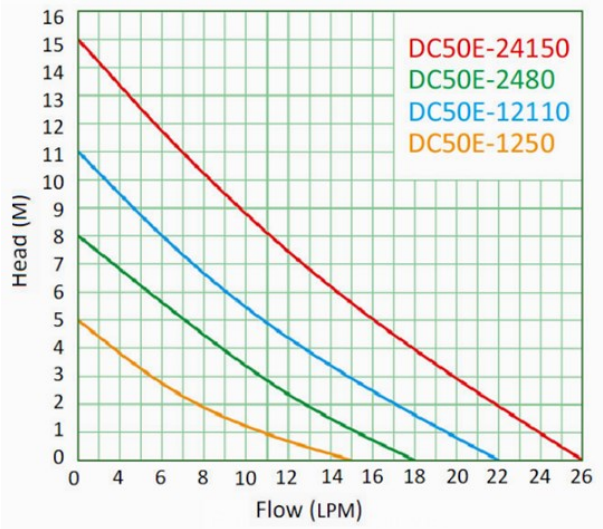


Fig. 3. The characteristic curve of DC50E-24150 series centrifugal pump [9].

The DC supply regulator is a DC-to-DC converter with a regulator signal in the form of a DC voltage range between 0-5 V. The BLDC motor drive and DC-to-DC converter combination are often referred to as the Electronic Speed Controller (ESC). This system obtains the ESC control signal from the Digital Analog Converter (DAC) output voltage on the amplified microcontroller.

C. Water Flow Sensor

The water flow sensor is a feedback signal to control the pump water discharge. This system uses a rotary-type water flow sensor with specifications as shown in Table 1. The output of the flow sensor is a pulse with a frequency proportional to the water flow. The relationship between output pulse frequency and water flow is formulated as in (15) [14].

$$Q_s = \frac{F_s}{11} \quad (15)$$

where Q_s is the flow of water passing through the sensor (l/min), F_s is the sensor output frequency. The sensor output pulse voltage matches the sensor's power supply voltage.

D. Microcontroller system

The drip irrigation pump discharge control system uses a 32-bit Advanced RISC Machine (ARM) microcontroller of the SAM3X8E ARM Cortex-M3 series. This embedded system module has a market name, Arduino Due. This microcontroller has 54 digital input (I/O) output pins (12 of which can be used as PWM outputs), 12 Analog to Digital Converter (DAC), 4 UART, 2 DAC, 2 TWI and a clock speed of 84 Mhz. Fig. 4 shows the address of the microcontroller pin connected to the supporting device. The supporting devices include a power supply, LCD, water flow sensor, solenoid drive and motor control signal amplifier.The LCD viewer has a 16 x 2 character display connected to the microcontroller via pins 23-33.

TABLE I. WATER FLOW SENSOR SPECIFICATIONS

Thread size	Male g 1/2"
Size	L 44x26.5mm
Flow rate	1~30L/min
Flow Pulse (Hz)	F(Hz)=(11xQ)
Working Voltage (V)	DC 5V~24V
Load Capacity (mA)	10 mA (DC 5 V)
Operating Temperature (C^0)	-25 C^0 to +80 C^0
Accuracy	5%~10%

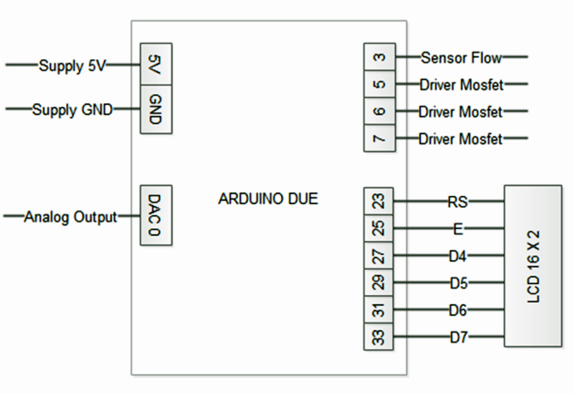


Fig. 4. Address of the microcontroller pin connected to the supporting device.

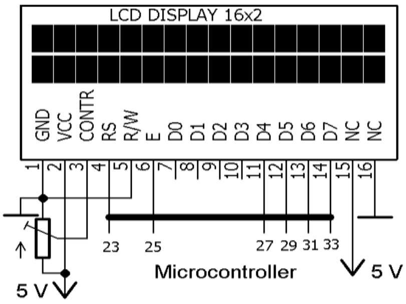


Fig. 5. Schematic integration of LCD to microcontroller.

LCD functions to display setpoints, water pump discharges and active solenoids. Fig. 5 is a schematic of the integration of the LCD to the microcontroller.

The microcontroller activates the solenoid valve through the driver in the form of a Mosfet transistor. The type of MOSFET transistor in this system is IRFZ44. This transistor is capable of carrying currents up to 30 A. The solenoid control signal is modulated with a frequency of 10 kHz and a duty cycle of 0.8. The modulation aims to increase the solenid impedance, reducing power consumption. Fig. 6 is a solenoid driver circuit using a transistor with biased input using an optocoupler. Optocoupler besides functions as an amplifier and optical isolator.

The control algorithm on the microcontroller generates a control signal to control the rotational speed of the BLDC motor. Because the motor control signal is analogue, the signal from the microcontroller in the form of digital data is converted to an analogue signal using DAC. The DAC on this microcontroller is 12 bits. The output voltage of the DAC has a minimum output of 0.55V and a maximum output of 2.75V. With an output range of 2.2 V, the DAC resolution is 0.5372 mV. The signal from the DAC must be amplified 2.27 times to match the input voltage range of the BLDC motor driver. The offset is also reduced to 0V. The differential amplifier circuit is used as in Fig. 7. Figure 8 shows the DAC output voltage before and after amplification using a differential amplifier. The output signal after amplification has an offset voltage of 0 volts and a maximum voltage of 5 volts at full scale. The DAC output is a control signal from the microcontroller. After being conditioned, the signal is in accordance with the standard input signal for the electronic speed controller (ESC).

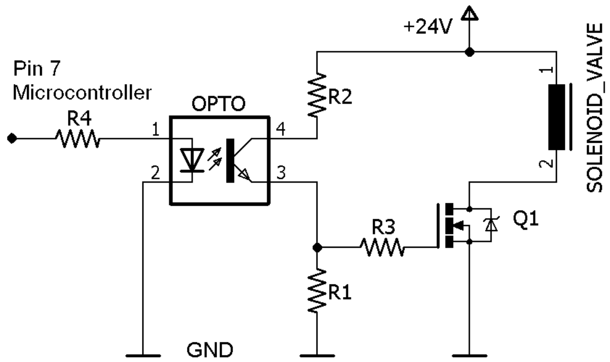


Fig. 6. Solenoid valve driver circuit.

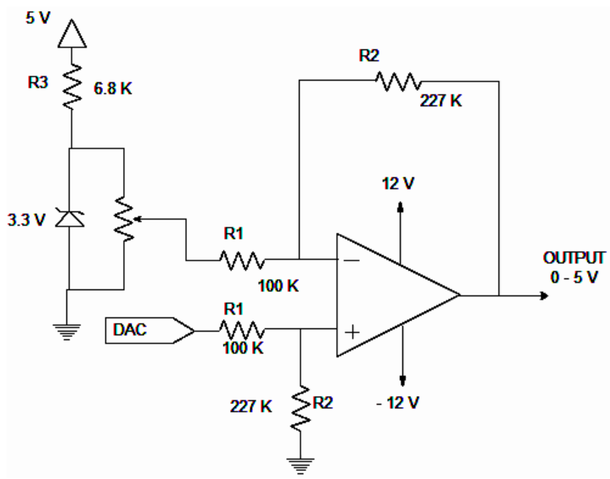


Fig. 7. Amplifier circuit for DAC.

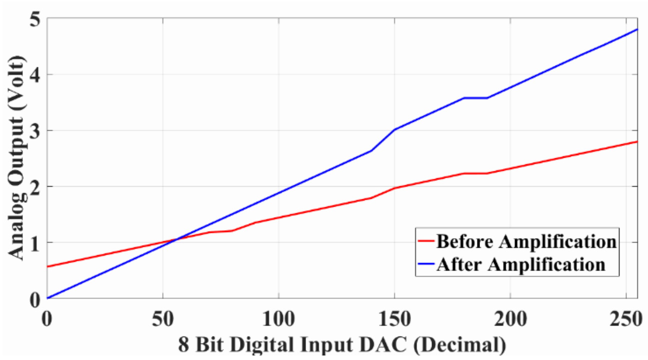


Fig. 8. DAC output voltage before and after amplification using a differential amplifier.

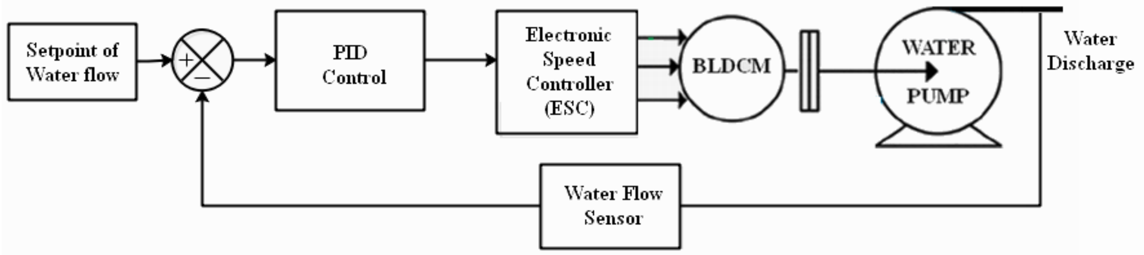


Fig. 9. Functional diagram of water flow control for drip irrigation.

E. PID Control method

The functional diagram of the water flow controller for drip irrigation in this study is shown in Fig. 9. The system uses PID control methods. The controller input is an error signal which is the difference between the setpoint and the flow sensor. The PID parameters were obtained using the Ziegler-Nichols method. This method is based on the system's response to an open loop indicated by the unit step function. The concept of determining the PID parameters is based on the system response curve, as shown in Fig.10.

The system response will form an S-shaped curve. In this curve, a line is made that is tangent to the curve line. The tangent line will intersect with the abscissa axis and the maximum line. The tangent line intersection with the abscissa axis is a measure of dead time (L), and the intersection with the maximum line represents the delay time (T) measured from the time point L. The results of the measurement are then entered into Table 2. The control strategy for this system is PID control. The results of testing the system in the open loop condition obtained a curve like Fig. 11.

After an approach using the Ziegler Nichols method, the value of L is 0.5, and T is 2.5 s. Based on table 2, the PID control parameters in this system are 6 for P, 0.048 s for Ti and 1.5 s for Td. The hardware of the water discharge control system in drip irrigation has been made as in Fig. 12.a. System testing is done through a series of pipes with closed water circulation as in Fig. 12.b. Another test is installing the system into a drip irrigation network with open water circulation, as in Fig. 13.

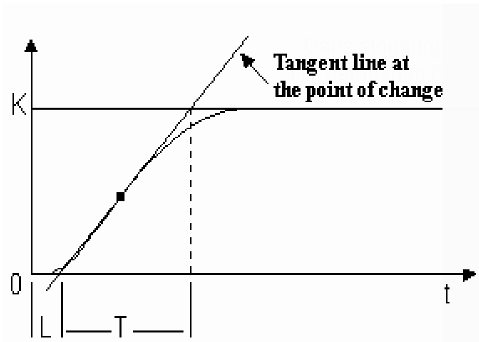


Fig. 10. System response curve and Ziegler and Nichols approach.

TABLE II. ZIEGLER NICHOLS TABLE

Controller Tipe	Kp	Ti	Td
P	T/L	~	0
PI	0,9 T/L	L/0,3	0
PID	1,2 T/L	2L	0,5L

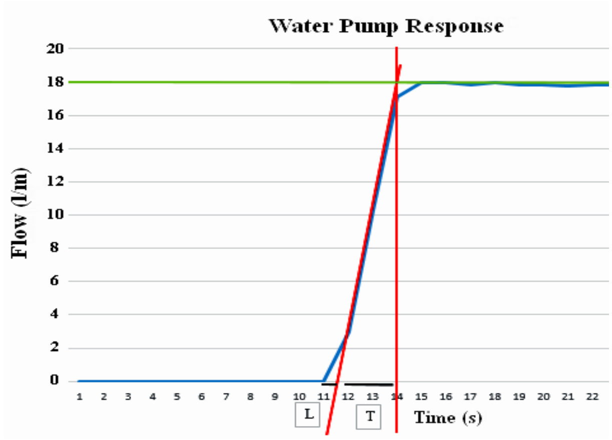
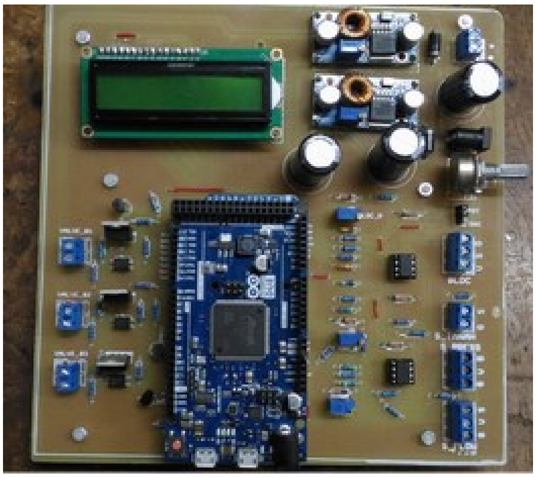
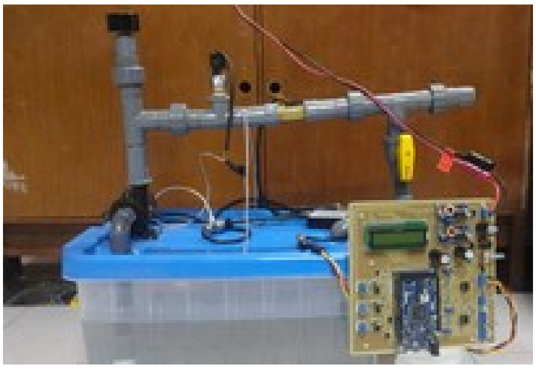


Fig. 11. The response curve of the water flows control system using the Ziegler Nichols approach.



(a)



(b)

Fig. 12. a) Hardware of the control system, b) Testing of the water flow control system in a closed circulating pipe circuit.

Fig. 13. The Testing of water discharge control systems on small-scale drip irrigation networks.

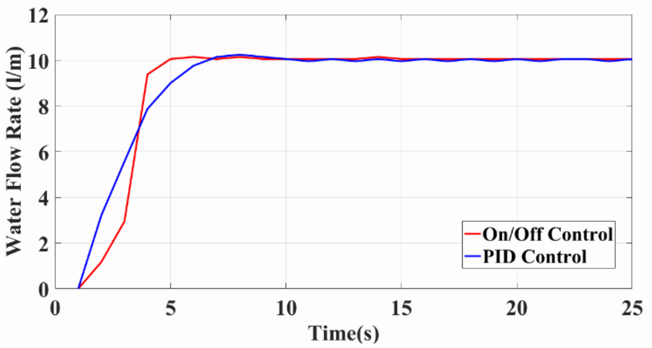


Fig. 14. System control response with the On-Off method compared to the PID method.

III. Results and Discussion

Experiments have been carried out to determine the characteristics of the control system. The first test compares the system with the on/off method compared to the PID method. The response of the two methods is shown in Figure 14. It can be seen that the PID control has a smoother and more linear response during the rising time. The system with PID has a small oscillation magnitude at steady state. Systems with on/off control produce non-linear responses during transients and steady-state oscillations to a greater extent than the PID method. Therefore, controlling pump discharge with the PID method has a better system response than the on/off method.

The second test aims to determine the pump controller's response if a disturbance causes the irrigation capacity to change. Disturbances caused by blockages in irrigation networks due to dirt and moss. Disturbances that result in changes in irrigation capacity are simulated by changing the position of the valve opening on the manifold pipe. The valve opening percentage is directly proportional to the increase in irrigation capacity. The valve opening varies between 40% and 100% in this test. The discharge setpoint value is 5 l/m.

Figure 15, Fig. 16 and Fig. 17 are the system response without a pump discharge controller. Figure 15 shows the response when the valve changes from 100% to 60%, Fig. 16 shows when the valve changes from 100% to 50%, and Fig. 17 shows when the valve varies from 100% to 40%. These responses indicate that the pump discharge changes when a disturbance occurs. This disturbance increases the pump head loss and results in reduced water discharge.

The system response with the PID controller is shown in Fig. 18 to Fig. 21. Figure 18 is the system response when the valve changes from 100% to 70%. Figure 19 is the system response when the valve changes from 100% to 60%. Figure 20 is the system response when the valve changes from 100% to 50%. Figure 21 is the system response when the valve changes from 100% to 40%. From the four responses, it can be seen that the water flow at the pump output is maintained at the setting point value. Although there is a decrease in flow rate when there is a change in valve opening, this occurs momentarily. The decrease in flow rate is due to the increase in pump head loss so that the discharge decreases. The controller's response is to increase the pump speed so that the discharge increases.

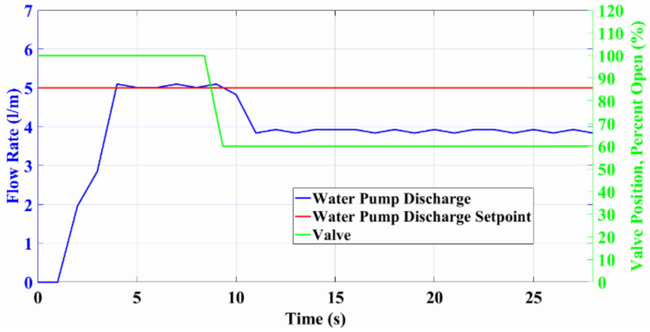


Fig. 15. Uncontrolled system response when valve openings from 100% to 60%.

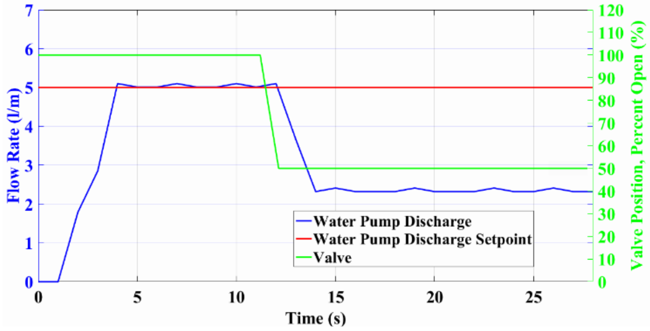


Fig. 16. Uncontrolled system response when valve openings from 100% to 50%.

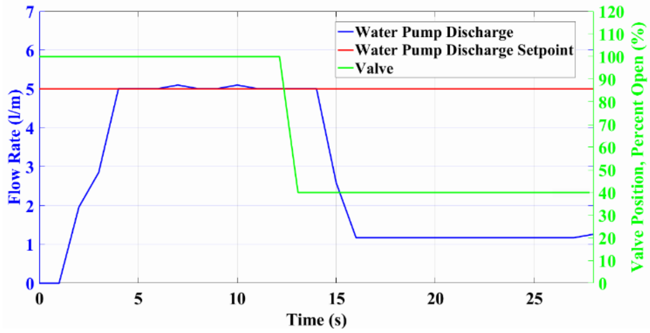


Fig. 17. Uncontrolled system response when valve openings from 100% to 40%.

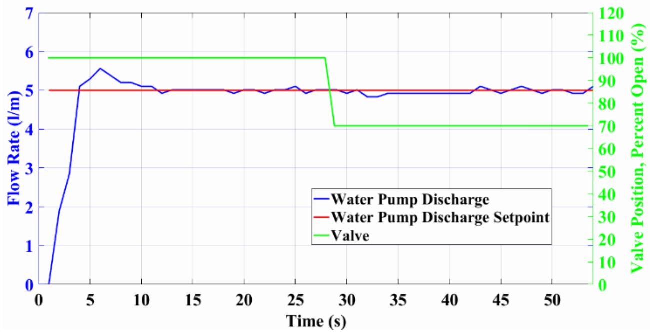


Fig. 18. System response when valve openings are from 100% to 70%.

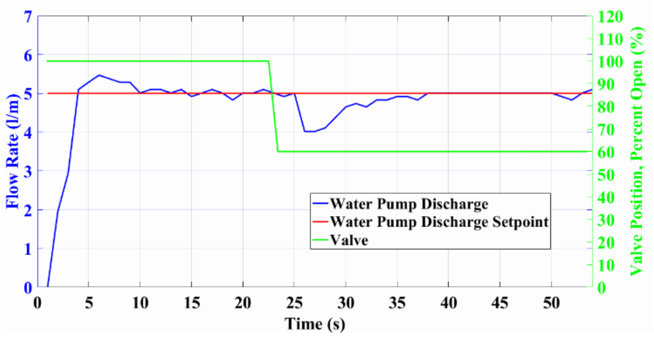


Fig. 19. System response when valve openings from 100% to 60%.

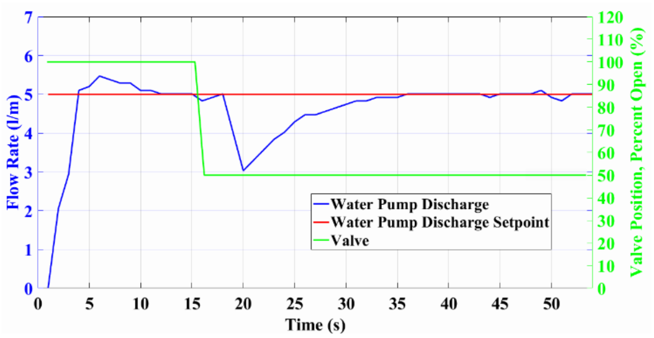


Fig. 20. System response when valve openings from 100% to 50%.

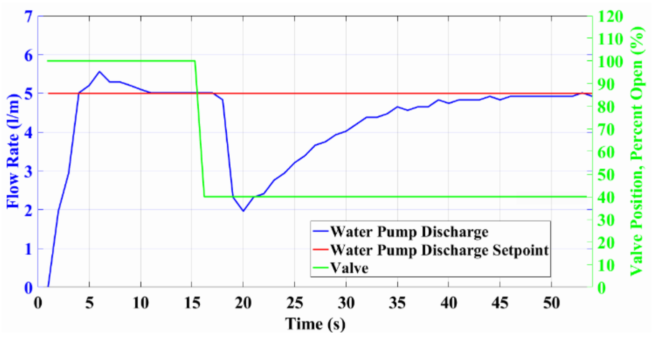


Fig. 21. System response when valve openings are from 100% to 40%.

The volume of water supplied to the plants is the multiplication of the irrigation duration and the emitter discharge, so fluctuations in the emitter discharge reduce irrigation accuracy. The stability of the pump discharge supplying the irrigation network makes irrigation more accurate, because the water discharge at the emitter is more stable.

IV. Conclusion

Water pump discharge control using the PID method produces a system that can maintain a stable irrigation flow rate. Changes in a head loss that are simulated by changes in valve opening are responded to well by the control system so that the flow rate is maintained constant. Determination of PID control parameters using the Ziegler-Nichols method is reasonably practical and straightforward. The correct selection of PID controller parameter values is essential because if the parameter values do not match, the controller's performance will be poor. Changes in irrigation capacity followed by changes in the appropriate flow rate setting point produce accurate irrigation.

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