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Full Length Research Paper

Prototype of a control system for trickle irrigation systems considering distributors' flow rate variation

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A prototype of a real-time closed loop automatic control system has been successfully developed to suit trickle irrigation systems management. The control system was designed to manage the irrigation system based on collecting data through soil moisture sensors located at three different locations acting each third of the lateral to put the effect of emitters' flow rate variation along laterals on soil moisture content distribution in consideration. Soil moisture content which will be used to start and stop the irrigation process will be based on the average of three sensors' readings. Required inputs to manage the irrigation system were soil field capacity (FC), permanent wilting point (WP), and percentage of moisture allowed depletion (MAD). Irrigation process will begin when the soil moisture content equals the desired percentage of available water and it will stop after reaching soil field capacity. The system was provided with ability to check some defects that are related to the irrigation system like clogging, poor uniformity, and water pumping failure. Laboratory assessment showed that the control system has applied the design considerations and is expected to save irrigation time if implemented with low or poor uniformity trickle irrigation networks when compared to high uniformity networks. The study recommended evaluating the effect of this control system implementation in field especially with trickle irrigation networks which show poor uniformity to use the potentials of the control system to predict emitter clogging, and poor uniformity which are mostly appear in such irrigation systems.

Key words: Automatic control, closed loop**,** flow rate variation, modern irrigation systems, real time.

INTRODUCTION

Due to the ability of modern irrigation systems in saving water, replacement of traditional irrigation systems with the modern systems tends to be a must especially in arid and semi-arid areas (Douh and Boujelben, 2011). This replacement may lead to excessive consumption of energy than traditional irrigation systems as they are the main element of energy consumption in agriculture (Hatirli et al., 2006). Trickle irrigation systems are considered water and energy-saving systems if compared to other modern systems like sprinkler irrigation. Automatic control can help trickle irrigation systems' operators to face the challenge of achieving successful management which will lead to efficient use of water and energy (Navarro-Hellín et al., 2016; Puerto et al., 2013). Upgrading conventional irrigation systems to intelligent systems can help in saving water up to 30%

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(Dassanayake et al., 2009). Automatic control systems are mainly relying on collecting climatic and/or soil data and analyzing them to predict the suitable irrigation scheduling according to the fed model or algorithm. Soil data has the advantage of describing the integrated effect of climatic data and cultivation management practices on irrigation requirements. Soil moisture is considered by many authors the key to successive irrigation scheduling (Cardenas-Lailhacar and Dukes, 2010; Soulis et al., 2015). Virtual sensing technique has become a very efficient and powerful tool to support the control techniques (Ponsart et al., 2010) which makes irrigation control systems that are based on moisture sensing devices more recommended. Moisture sensing devices are useful tools for collecting the required moisture data in the root zone considering the effect of water consumption by plants, soil properties and climate effect (Vereecken et al., 2008). Closed-loop control system has increasing interest and wide implementation in irrigation systems during the last years. The studies of Kim et al. (2008, 2009), Li et al. (2011), Constantinos et al. (2011) Pfitscher et al. (2012) and Stefanos et al.(2015) indicated the importance of closed-loop control systems based on on-line soil moisture monitoring for reaching efficient use of water and energy. It has been remarked that all of these studies tend to narrow the gap between the management scenarios that will be implemented by the control system and the real water needs for plants. Also, these studies depended on collecting moisture data from one certain point or several points through the field without considering any common problems that accompany system operations like distributors clogging or poor hydraulic performance. Irrigation system operation if based on the information collected from one point along lateral will face the problem of the possible significant variation between distributors' application rates which may lead if neglected to over or deficit irrigation as a result of the deceptive measurement of soil moisture content. The objectives of this work were as follows:-

1. Develop a prototype of a real-time, closed-loop control system based on soil moisture monitoring to manage trickle irrigation systems considering distributors' flow rate variation along lateral. The system will be provided with monitoring features to predict some problems that may appear during irrigation system operation like clogging, poor hydraulic performance, loosing sensor's signal, and water pumping failure.
2. Predict the effect of using the proposed control system on operation time for trickle irrigation system whether showing good or poor hydraulic performance.

MATERIALS AND METHODS

The control system was developed by Elnemr (2017). The proposed control system is a real time closed-loop control system. The system design was mainly going to be compatible with trickle irrigation systems. Laboratory assessment has been in operation since the year 2018 in the Department of Agricultural Engineering, Damietta University-Egypt to test how the system can apply the design considerations. The proposed control system was designed to manage the irrigation system basing on monitoring soil moisture content through sensing devices distributed along lateral And to be established at three points acting each third of the lateral. The average of the three moisture content values will act the current soil moisture content. This is supposed to consider the variation in the distributors' application rates which may help to avoid over or deficit irrigation.

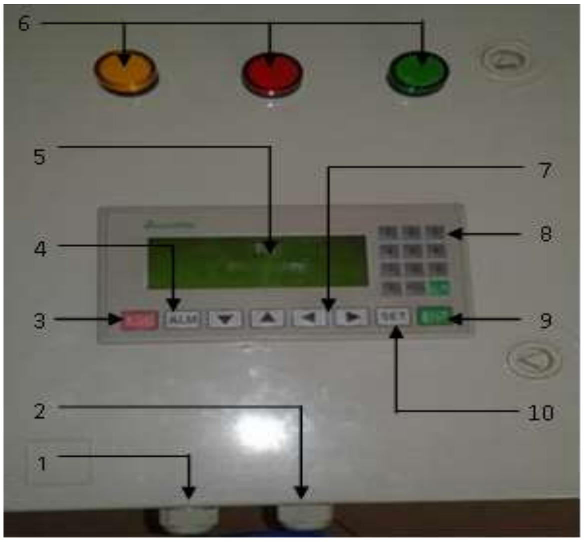

Figure 1. Control system containing box and interface components. 1- Control unit power input cable path, 2- Sensors signal and pump power cables path, 3- Escape button to get out of a menu, 4- Check errors button (ALM), 5- Digital screen, 6- Sensors' signals indicator, 7- Transfer buttons, 8- Numeric input buttons, 9- Data Entry confirmation button, 10- Input and system settings menu button.

General description and hardware construction

The control system appears in a containing box 400 mm height, 300 mm width, and 170 mm depth. Hardware was mainly divided into three parts which are operation panel, data processing and control sets, and three soil moisture sensing devices that will be fitted along trickle irrigation lateral. Control system interface is shown in Figure 1. Two main paths on the lower edge are allocated for the system feeding current and irrigation pump connection cables. The other one is for sensor feeding current and signal cables. The interface included digital operation panel (Touchwin OP320-A) which is composed of digital screen in addition to numeric buttons. The operation panel was connected to a Programmable Logic Control unit (PLC, Fatek FBs-B4AD to enable the user to enter the required inputs to the PLC in addition to showing system operation data. Three indication lamps were fitted in the containing box each of them indicates whether the control system is receiving a sensor signal or not.

Data processing and control sets included wire terminals, conductor to control the feeding of any desired irrigation pump with electric current to switch it ON or OFF according to the order received from the PLC, AC adaptor to reduce the 220V electric

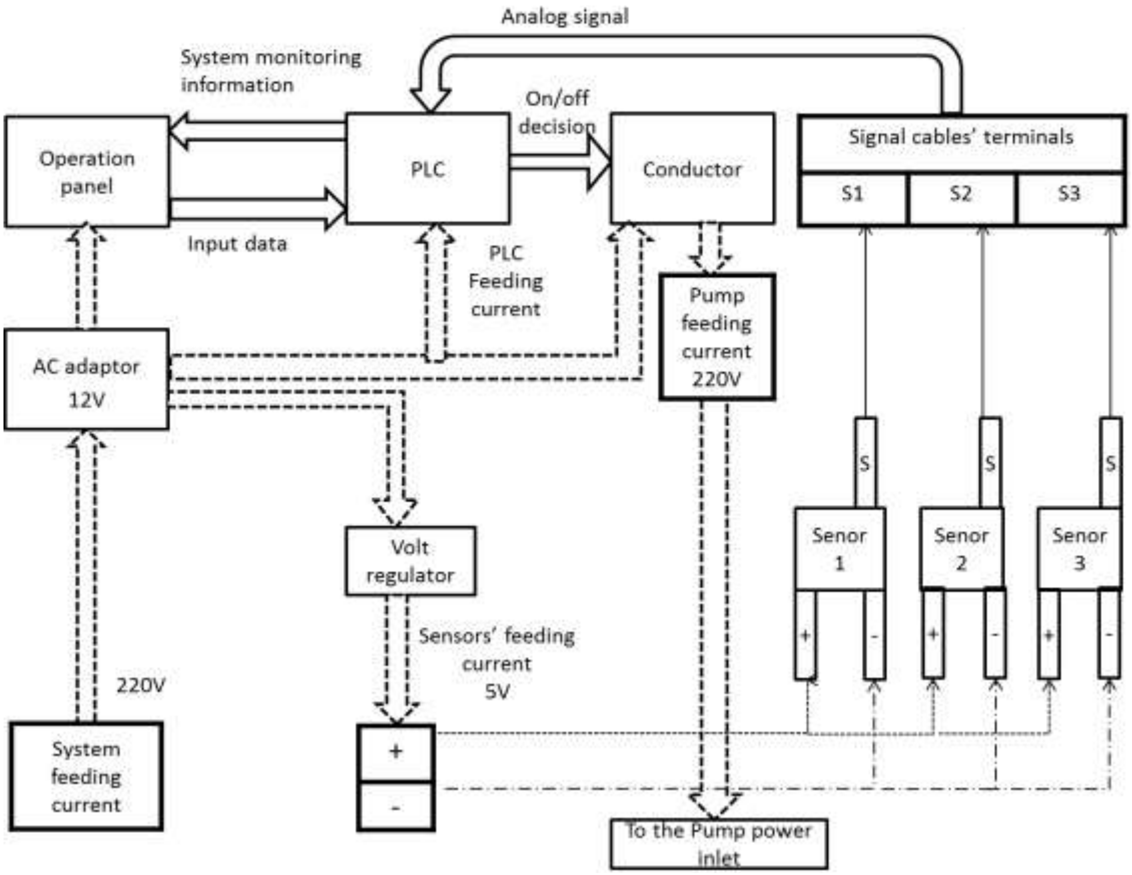

Figure 2. A diagram for the control system hardware. S= Sensor output signal.

Table 1. Technical specifications of the used sensors referring to Manufacturing data.

Brand	Supply voltage	Output voltage	Working current	Output Signal
Funduino	5V	0-2.3V	Less than 20A	Analog

potential difference to 12V which is suitable for the PLC. A volt regulator was connected to the AC adapter to keep feeding the sensors with required potential difference (5V). Figure 2 describes the hardware components and their connection with each other.

Manufacturing data of the used soil moisture sensors are listed in Table 1. Each of the sensors has three connections, two of them are the electrodes (negative and positive) and the third one was for signal transfer. All these connections were made through a three wires shielded cable. Analog signals of the sensors were transferred to the PLC to be processed according to the system software design and algorithm. Analog signal of the sensors was converted to digital signal to be fed to the PLC through analog to digital converter ADC.

Design considerations and software preparation

Design considerations and required data processing was fed to the PLC unit through its own open source program Irrigation system operation management will base on the reading of soil moisture sensing device as mentioned before. In addition to this point, system software was designed to apply the following considerations:-

1. The required inputs are field capacity (FC), permanent wilting point (WP), and moisture allowed depletion (MAD) which is a factor that is related for both soil and crop properties as they are essential data for irrigation management practices (FAO, 1998).
2. The control system will be able to transfer between manual or automatic modes. Manual operation mode will give the flexibility to the users to operate the system in case of sensors malfunctioning or other purposes like irrigation network testing, flushing, etc.
3. The control system will be provided by a monitoring technique to warn the user of certain problems whether related to the control system (moisture sensors malfunction) or the irrigation system including poor uniformity conditions, and water pumping failure.

Irrigation system operation and criteria of ON/OFF decision

Figure 3 shows the flowchart which describes the control system's algorithm. The user will have the ability to choose between manual (M) or automatic mode (Au) in the beginning of operation. In case of choosing manual mode, the user will be asked to enter the required operation time (T) in hours with 1-digit accuracy. In case of Au mode, the user will be asked to enter the values of FC, WP, and MAD. All these values will be fed to the system as percentages with two-digit accuracy. System will automatically check the existence of sensors signals to point it out to the user through indication lamps. Current soil moisture content value (MC) will be considered as the average of the three readings of the sensors. In case of losing one or two signals from the sensors, the system will calculate MC as the average of the rest signals. This means when the control system receives just two signals, the system will change the way of calculating MC to be the average of these two signals. In case of receiving just one signal, it will act the MC directly. MC_{on}, the MC at which the control system will take the decision of starting the irrigation process were calculated according to the following equation:

$$MC_{on} = (FC - WP)\left(1 - \frac{MAD}{100}\right) \qquad (1)$$

The control system was designed to start the pump after the depletion of the allowed percentage of water moisture from the soil and stop after reaching the FC.

Technique of monitoring and checking irrigation system defects

The control system was provided with the advantage of checking sensors signal as earlier clarified. This feature will enable the system to keep the irrigation process running with minimal errors due to excluding the absent signals of the damaged sensor(s) from MC calculation. If the three signals were lost, the system will turn automatically to the manual mode. When losing any of the sensors' signals, its indication lamp will flash to clarify the responsible sensor for the error. The control system will record the increase in moisture content based on the received signals from each sensor after starting irrigation process for 15 min. If there is no increase in soil moisture content at any of the sensors, as the possibility of distributors clogging, the sensor error lamp will light. If the soil moisture reading is stable for the three sensors together, then there is a high possibility that the pump is not working properly. The control system will hint the user by "pump error" message on the digital screen. Also, the control system will monitor the variation of the increase in soil moisture between the three points. If the variation between soil moisture content of the three points exceeds 25%, the control system will assume that the system is working in unacceptable level of uniformity and will alarm the user by "system error" message on the digital screen. The value '25%' was cited from Anyoji (1993) who clarified that flow rate variation at this percentage may mean that the system is working under fully turbulent flow conditions and emitter exponent equals 1. In cases of pumping or irrigation system defect, the control system will turn automatically to manual mode as shown in Figure 3. The decision of turning to the manual mode in the cases of losing all sensors' signals, high flow rate variation, possible clogging, or pumping failure is taken by the control system to avoid over or deficit irrigation due to wrong calculations expected in case of such exceptional circumstances. This also gives the user the opportunity to take his maintenance procedures. The control system takes the pumping off decision when MC value equals the FC value. System interface has an alarm button (ALM) to check the system and display the existence of any of the previously mentioned errors.

Operation panel data

Functions required to be shown on the digital screen and those of numeric button are fed to the system through the open source software. Digital screen was designed to show the operation data and guide the user for the buttons he can use to transfer between operation modes, entering data, and check the system errors as shown in Figure 4. Shown operation data included calculated MC value, total irrigation time and the selected operation mode. Any errors fed back to the control system can be displayed on the digital screen by alarm button (ALM) as shown earlier in Figure 1.

System test

Laboratory assessments are being performed to test the ability of the control system to apply the design considerations. Assessments include testing the manual mode, moisture content calculations, system error detection, and field work simulation to state how successfully the proposed control system can adjust the irrigation system operation time. Electric centrifugal water pump 0.5 hp (0.37 kW) - 220V was connected to the system to examine the accuracy of ON and OFF pumping decisions according to the control system design considerations.

Testing manual mode

The control system was adjusted to work on manual mode for 2, 10, and 20 min. The operation time of the pump was calculated using a stopwatch to be compared to the required time.

Sensor calibration

Twelve wetted clay and sand soil samples were used in order to calibrate the sensor reading with the real soil moisture content. Gravitational method was used to determine the wight-based soil moisture content. Moisture content read by the sensors was shown on the digital screen. Soil samples were put in steel pots 500ml each, water was added to soil and the wetted sample was left for 24 h to assure the moisture homogeneity in the sample.

Three similar soil moisture sensors of the used type were connected to the control system one by one to give a read of soil moisture content. This means each of the sensors was used with 8 soil samples varying between clay and sand soil. After obtaining the reading of MC from the sensors, soil samples were put in drying oven for 24 h at 105°C.

Data was fed to curve expert software (Version 1.34) to obtain the required formula. Weibull model resulted as follows:

$$S = 79.13 - (148.69 * e^{-0.98M^{0.44}}). \quad R^2 = 99.94 \qquad (2)$$

Where

S= Sensor soil moisture reading %; M= Real weight-based soil moisture content, %.

Automatic mode test

Automatic mode was tested in order to examine the ability of the system to take the ON/OFF decision of the irrigation system according to the design considerations. Sensors were immersed one by one in three 500-ml steel pots filled with wet clay soil. Initial average moisture content reading of the sensors was assumed to be the wilting point and it was fed to the system to assure the response of the system to take the ON decision. FC was assumed as 40% which equaled 78.1% of sensor reading according to Equation 2. MAD value was 30%. Water was applied for the three pots gradually till the MC reading on the digital screen reaches

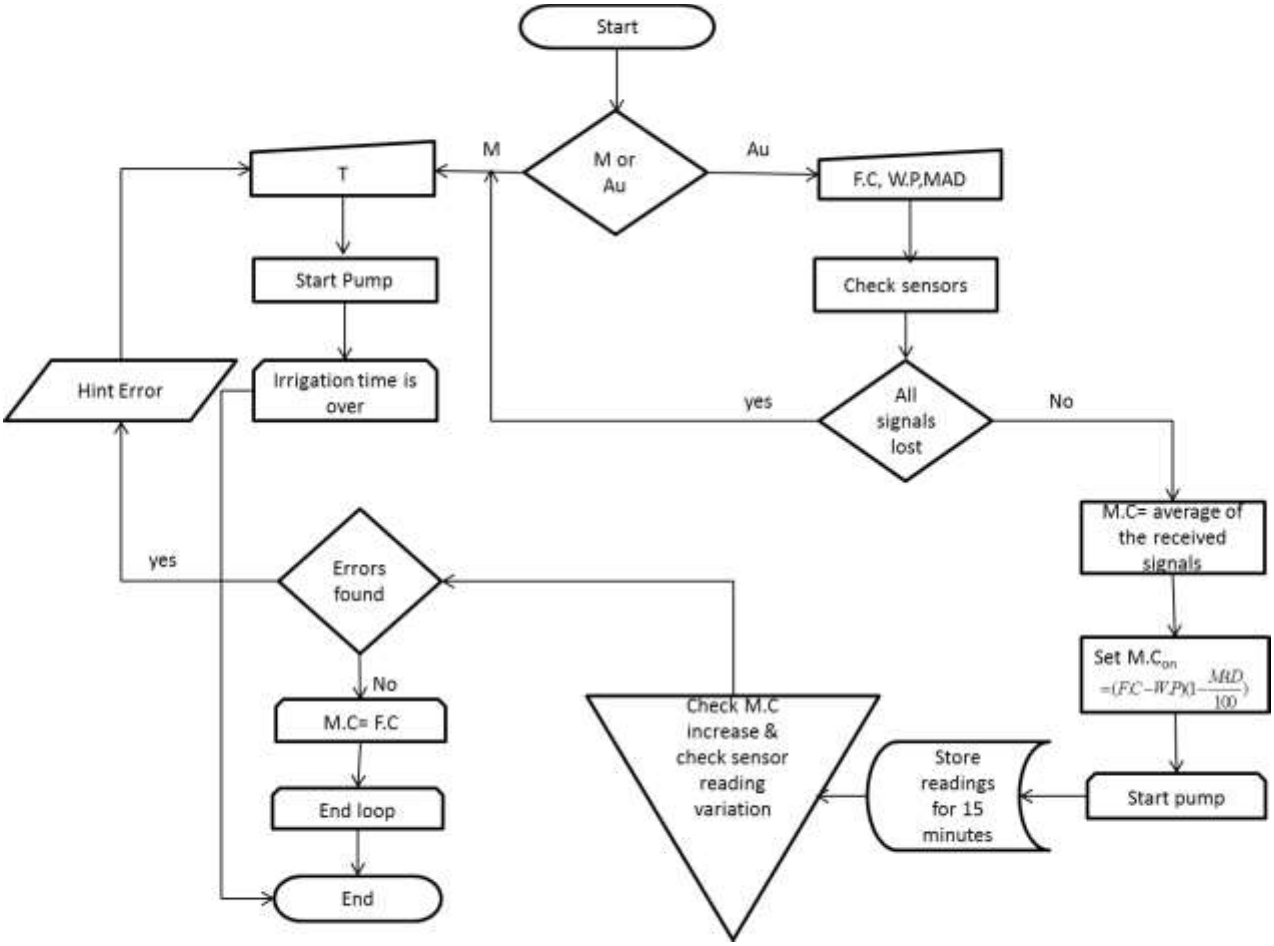

Figure 3. Flow chart of the control system's software.

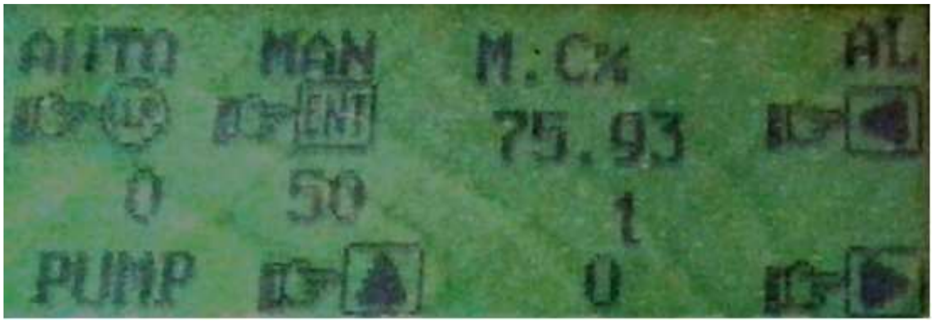

Figure 4. Moisture content value and operation data shown on the digital screen.

equivalent reading for the entered value of FC. After finishing the previous test, the readings of the soil moisture content on the panel screen were recorded. Wires of the sensors were unplugged one by one to monitor the change in soil moisture content average calculation due to the change in received signals.

Predicting possibility of clogging or pumping failure

Each of the three soil moisture sensors is proposed to be fitted under one water application point of the irrigation system. If this distributor is clogged at this point, the received reading of soil moisture will affect the accuracy of irrigation system operation decisions. In order to test the ability of the control system for predicting clogging, each sensor was connected individually to the control system and immersed vertically in a pot containing soil without adding any water to avoid the increase in moisture content for 15 min. The three sensors were connected to the system, immersed vertically in the pots and kept without increase in moisture content for 15 min to examine the ability of the control system to predict possible pumping failure. Testing system ability to predict clogging possibility or the high variation between distributors' application rates was conducted by connecting just two sensors to the PLC. The two sensors read the average initial moisture content of the soil in the pots. One of the soil samples was kept dry and water has been applied slowly to the other one till increasing the MC reading by 12.5% which gives a difference in moisture content of 25% between the two soil samples.

Field work simulation

Data collected from a field experiment by El-Nemr (2013) using drip irrigation system was used to calculate the expected variation in irrigation duration when using the control system compared to the calculated irrigation time of the mentioned study based on the average flow rate of 20 emitters. Two scenarios were simulated by selecting three sensor positions from each one-third of lateral. The first case is selecting three emitters which have the nearest flow rate values to the average flow rate to act as highly uniform emitters' flow rate distribution (U_h). The second involves selecting the farthest emitters from each one-third of the laterals to the average flow rate of emitters along the lateral to act as the poor uniformity drip irrigation networks (U_l).

RESULTS

Manual mode operation

The results show that the operation time of the connected pump was exactly the same input time. The system was able to stop the pump operation at the time required by the user.

Automatic mode operation

The control system is able to calculate MC based on average of the three sensors' signals. Variation in the number of signals received from the sensors was faced by an accurate calculation for MC by the control system according to the design procedures.

The control system started the pump directly after finishing automatic mode inputs settings. This was because the initial moisture content was 15.8% which equals the sensor reading of 76.01%. This value is less than the proposed MC to start the pump (19.6%) and equals the sensor reading of 58.88%. The system interacted accurately with the change in soil moisture signals received from the sensors. The OFF decision of pumping was when MC equaled the fed value of FC.

Predicting clogging and pumping failure

The control system showed a response to the possibility of distributors clogging and pumping failure. As there was no increase in MC value for 15 min after starting the pump, the pump has been turned off and the control system showed the message "Pump error" on the digital screen" and was ready for time input in the manual mode. There was also a response for the high variation in application rates of the system and showed the message "system error" on the digital screen.

Effect on irrigation time

Data listed in Table 2 show the expected variation in network operation time due to the use of the proposed control system referring to the results of field work simulation. The two scenarios of irrigation network operation showed that using the control system in its default case (receiving the three sensors' signals, $S_1+S_2+S_3$) is expected to increase the operation time in both U_h and U_l scenarios. The cases of signal absence showed that U_h will record an increase in operation time in the cases S_1+S_3, S_2+S_3, S_2, and S_3 while S_1+S_2 and S_1 will show a decrease in operation time. The U_l network scenario showed increase in operation time in cases S_2+S_3, S_2, and S_3 while it showed a decrease in operation time in the other cases. Applying U_h and U_l scenarios revealed that the control system helped to decrease the operation time of the irrigation network for the U_l if compared to U_h in cases of receiving all signals, S_1+S_2, S_1+S_3, and S_1; whereas it was higher in cases of S_2+S_3, S_2, and S_3.

DISCUSSION

Results obtained from the laboratory assessment showed that the introduced prototype has applied its design considerations successfully. Manual modes succeed in operating the connected pump for identical time as required. Automatic mode operation gave the ON decision according to the design calculations and gave OFF decision at the entered FC value. During the tests, the MC of ON decision was not exactly as the proposed one. This is because the MC value in the beginning of the test was (15.8%) which is lower than the proposed one (19.6%). It was not possible to adjust the initial MC of the used soil sample or monitor the actual moment at which MC of the soil reaches the proposed MC to start the system, the control system reaction is considered acceptable and indicates the ability of the system to start the pump at the required MC value. To keep this accuracy of the control system, it is essential to recommend making calibration for the sensors when the sensors are changed or moved to the field as recommended by Girisha et al. (2012) due to the sensors' expected poor accuracy. The ability of the control system to predict the possibility of distributors clogging or water pumping failure, besides detecting the high variation in distributors flow rates in addition to system user alert function, is considered a protective

Table 2. Expected variation percentage in operation time based on the possibility of losing sensors signal compared to field work

Scenario	S_1+S_2+S_3	S_1+S_2	S_1+S_3	S_2+S_3	S_1	S_2	S_3
U_h	1.85	-0.26	2.37	4.00	-1.58	1.06	6.33
U_l	0.53	-6.86	-1.58	10.29	-18.73	5.01	15.57

maintenance tool for both the irrigation system and the control system. These features prevent the control system from operating the system with deceptive data from the monitoring points. It gives also an indicator to the user about possible defects in his irrigation system performance whether were related to system components or management. This helps in achieving one of the main purposes of automatic control which is saving water and energy in a better way. Field work simulation showed that the control system had an effect on operation time whether by decrease or increase. Modification in irrigation system operation time is expected because of the difference in emitters' average flow rate of the used field data and the control system calculations considerations. Results of expected difference in operation time showed that the control system caused an increase in operation time in case of U_l networks in 4 cases, while the increase with U_h networks was in 5 cases. In the default case of the system when all the signals are received, the control system showed lower increase in operation time at U_l when compared to U_h. These results imply that the control system helps in saving irrigation time of low uniformity networks in most cases than the high uniformity networks, which will be followed by increasing water and energy use efficiencies. In addition to this expected feature, the ability of the control system to continuously monitor the soil moisture under distributors make it possible for the system to predict the emitters' clogging which is one of the expected phenomena in U_l trickle irrigation systems (Yavuz et al., 2010). Also, the prediction of emitter clogging will help to lower the operation costs and increase the system efficiency (Qingsong et al., 2008). As previously discussed, a consideration of the features introduced by the proposed control system and the higher possibility of saving water in case of low uniformity trickle irrigation networks has shown that the system can be more recommended to be used in low uniformity networks to take advantage of the potentials of the control system to predict emitter clogging, pump failure, and operation time modifications in case of losing one or more sensors' signals.

Conclusion

The proposed prototype of a real-time closed loop control system has been successfully developed to control trickle irrigation system operation. The control system was able to take ON/OFF decisions according to the design considerations whether in automatic or manual mode. It had the flexibility to deal with the change in the MC value which is used in system operation if there was any lost signal from the sensors. System monitoring features showed the required response to alert the user about possible clogging, poor uniformity, or water pumping failure. These features were considered important as a protective tool to make any required maintenance to the sensors or the irrigation system to assure achieving the desired impact of using the developed automatic control system. Field work simulation results showed that the control system will make a variation in irrigation time whether working with high or poor uniformity of distributors' flow rates. The control system showed lower increase in irrigation time at poor uniformity networks than the high uniformity networks. In case of losing one sensor signal or more, the control system was able to decrease operation time in most cases for poor uniformity networks. According to the obtained results, the proposed control system is able to apply the design considerations and it is recommended that the impacts of system implementation in the field especially with poor uniformity trickle irrigation systems be evaluated. Field studies should also include tries to investigate the most suitable position of sensors along laterals according to distributors' characteristics and performance.

CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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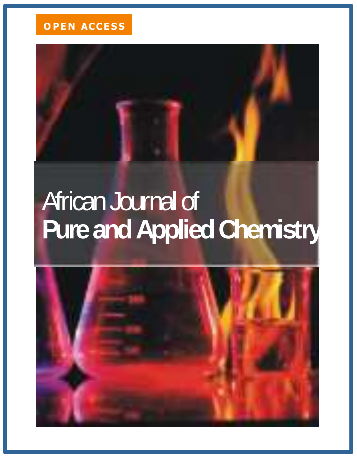

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