AUTOMATIC DOWNSTREAM CONTROL FOR CANAL HEADWORKS PUMPING PLANTS

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ABSTRACT

The application of the automatic downstream control concept is described as a feasible approach to upgrading the manual operation of the canal headworks pumping plant that delivers water to an open channel conveyance system. The water level in the canal downstream (usually located immediately upstream of the first downstream canal check gate structure) is used as the primary signal to automatically start and stop individual pumping units as the water demands downstream increase and decrease. Two modes of control are used: (1) the multistage, ON-OFF, two-position control is used for automatic operation of the smaller pumping units, and (2) the P+PR (proportional plus proportional reset) mode is used for the control of the next larger units. The two modes of control are discussed. It is shown how the two modes of control are combined for automatic operation of the canal headworks pumping plant that will assist the operator in maintaining a balance between the variable downstream demands of the canal distribution system and the canal inlet supply.

INTRODUCTION

Main canal systems serving numerous canalside turnouts that have complex irrigation schedules are being equipped with automatic downstream controls systems for the canal check gates. Automatic downstream control, using the control system known as the EL-FLO (Electronic filter level offset) plus RESET currently in operation on the Corning and Coalinga Canals in California, will maintain a balance between the canal demands downstream and the canal inlet supply. The EL-FLO control system is designed to be responsive to changes in canalside demands with a high degree of self-regulation, i.e., requiring virtually no supervisory intervention [1] [2]*.

If the canal headworks consist of gravity flow through a gated outlet structure, the method used for automatic downstream control of the canal check gates can be extended to include the headworks gate. However, if the canal headworks consists of a relift pumping plant, special considerations must be included when automatically controlling pumping units. Unnecessary pump starts may occur which increase maintenance costs. In addition undesirable water level fluctuations in the canal reach downstream may result if the control parameters are incorrectly selected. Provisions must also be incorporated to prevent the peak pumping rate from accidently exceeding the scheduled water and power supply for the headworks pumping plant.

Automatic operation of the main canal headworks pumping plant can be successfully achieved through the application of available control schemes currently being used for automatic pressure pipe distribution systems and for the automatic downstream control of canal check gates. Pressure pipe distribution systems use the multistage, ON-OFF, two-position mode of control to automatically start and stop pumping units based on a water-level change in a downstream regulating reservoir or tank [3]. The ON-OFF mode of control has been used (on a limited basis) for automatic control of one or two small pumping units at canal headworks pumping plants. Automatic downstream control known as the EL-FLO control system has been successfully implemented for the control of canal check gates using the P+PR (proportional plus proportional reset) mode of control [1] [2].

A recent study made by the United States Bureau of Reclamation combined the two modes of control, ON-OFF and P+PR, and developed a feasible automatic downstream control system for canal headworks pumping plants. The developed control system is currently being installed at the PVPP (Pleasant Valley Pumping Plant), the headworks for the Coalinga Canal located near Coalinga, California.

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* Numbers in brackets refer to literature cited.

The need for automatic downstream control of the canal headworks pumping plant is discussed. A description of the automatic downstream control concept and the general theory including selection of control parameters of the ON-OFF and P+PR control modes is given. The design strategy and the operation of the combined ON-OFF and P+PR modes of control is then presented. Finally, the advantages, disadvantages, and summary and conclusions are offered. This paper does not include technical descriptions of the equipment necessary to implement the ON-OFF, P+PR control system.

THE NEED FOR AUTOMATIC DOWNSTREAM CONTROL OF CANAL HEADWORKS PUMPING PLANTS

An operator of a main canal system has the responsibility of maintaining a balance between canalside turnout demand or orders and canal inlet flow. Precise scheduling is very difficult to implement on a total system basis. It is impossible to predict or anticipate some of the causes of turnout variation such as power and equipment failures. Prompt corrective measures are required to adjust intermediate check gates and the flow at the head of the canal to protect the system from serious shortages or surpluses of water propagating into the lower reaches of an irrigation canal system which usually have smaller carrying capacities.

Operating the canal headworks in the conventional mode, manual operation, would require 24-hour operator attendance when the canal check gates downstream are automatically controlled. The first canal reach between the canal headworks and check No. 1, figure 1, will be very sensitive to changes of demands downstream. The water level in the first reach could fluctuate to unacceptable values if the canal headworks is not responsive to the changes of flow that occur automatically at check No. 1. An operator, when operating the canal headworks manually, would have to continuously monitor the water level in the first reach and start and stop pumping units to maintain a balanced supply. Prompt action by an operator to adjust for the variable demands would not be as critical if the first canal reach consisted of a regulating reservoir. The variable demands could temporarily be absorbed by the storage capacity of the reservoir. However, the first canal reach is usually a typical canal section having very little storage capacity and designed for a maximum flow capacity based on the requirements of the irrigation distribution system.

Automatic downstream control systems for canal check gates can be designed to provide service on demand and respond to emergencies, such as sudden and abrupt changes of canalside pump turnouts, without affecting deliveries downstream. Automatic downstream control ensures sensible coupling of the irrigation demands and the canal inlet flow and is applicable to demand-oriented supply systems.

There is, therefore, a definite need to include automatic downstream control for the canal headworks. Automatic downstream control of the canal headworks will complete the coupling of the canalside demands downstream to the source of supply.

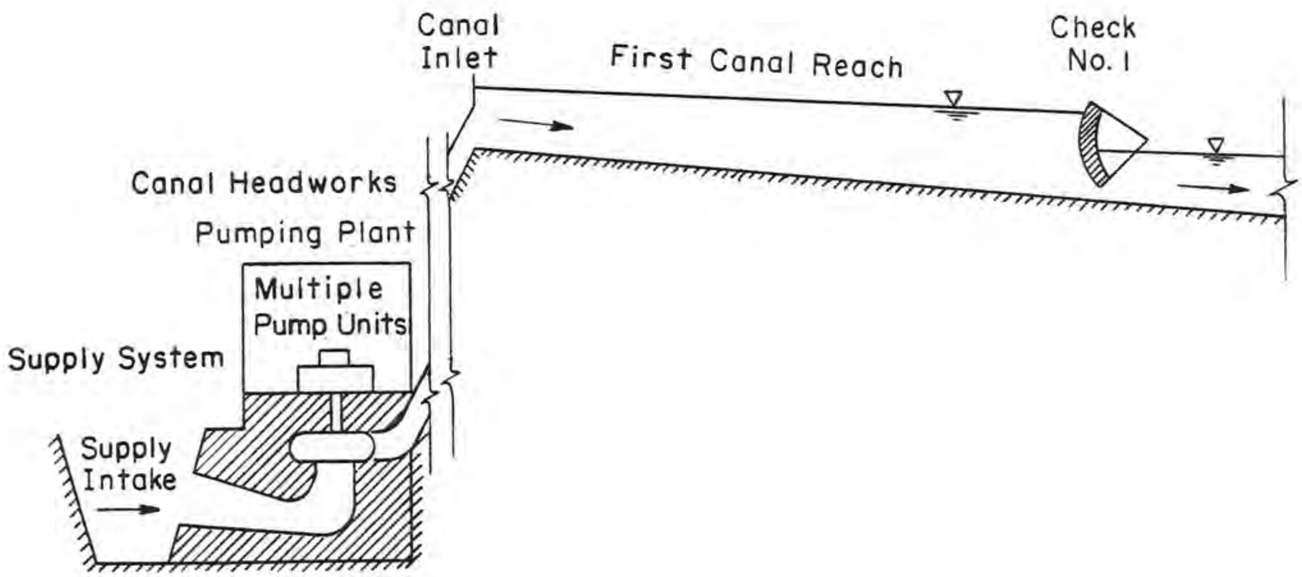

FIGURE I-SCHEMATIC PROFILE OF CANAL HEADWORKS PUMPING PLANT AND FIRST CANAL REACH DOWNSTREAM

AUTOMATIC DOWNSTREAM CONTROL CONCEPT

The downstream control concept is "the transfer of the downstream water demands from the point of use to the upstream source of supply." Downstream control is applicable to demand-oriented delivery systems. Applying the downstream control concept to a main canal system of an irrigation project means the downstream water demands being delivered through the many canalside turnouts en route are transferred upstream to the canal headworks or the source of supply. Automatic downstream control automatically transfers the downstream demands upstream through intermediate canal check gate structures to the canal inlet without supervisory intervention.

Main canal systems for irrigation projects are designed and constructed to deliver water to irrigation lands downstream from a source of supply upstream. The main canal begins with a maximum designed flow capacity and usually ends with a much smaller capacity as water is delivered through the many canalside turnouts to project lands en route (typically the end capacity is about 10 percent of the beginning capacity).

An important factor involved in the efficient operation of an irrigation project main canal is the delivery of specified amounts of water to the point of use at the times needed. Sudden and unannounced variations in canalside demands or mismatches (when the demand is larger or smaller than the supply) must not be allowed to propagate into the lower canal reaches that have the smaller carrying capacities. Serious shortages would cause objectionable water level drawdown and would disrupt service to water users; surplus water would cause flooding and trigger undesirable operation of the canal wasteways wasting water into natural channels [1]. The wasting of water as a result of operational errors is an inefficient use of the available water supply. Prompt action is required to adjust intermediate gates upstream and the canal inlet flow to maintain a balanced system and an efficient operation.

Irrigation main canals operated as a demand-oriented delivery system will achieve optimum efficiency of the use of available water supply. Automatic downstream control insures sensible coupling of the irrigation demands and the canal inlet flow.

THE ON-OFF CONTROL

The ON-OFF, two-position mode of control (referred to as "ON-OFF control") as it applies to automatic downstream control of the canal headworks pumping plant, starts and stops individual pumping units based on the change of the water level usually located at the downstream end of the first canal reach (immediately upstream of the first canal check gate), figure 1. The ON-OFF control mode is used for the automatic downstream control of pipe distribution system from main canal systems [3]. The vertical motion of the water level is monitored by the sensor. The minus and plus deadband from the target level (usually the water level at the maximum designed capacity of the canal reach) is detected by a comparator to determine if the pumps should be turned ON or OFF, thus two-position control. For automatic downstream control, when the water level lowers a specified amount signifying an increase in flow demand at check No. 1, the pump units are automatically turned ON to balance the inlet supply to the downstream demand. The pump unit is automatically turned off when the water level rises a specified amount signifying the canal demands are decreasing or the supply is in excess of the demand downstream. Figure 2 illustrates the ON-Off, two-position control.

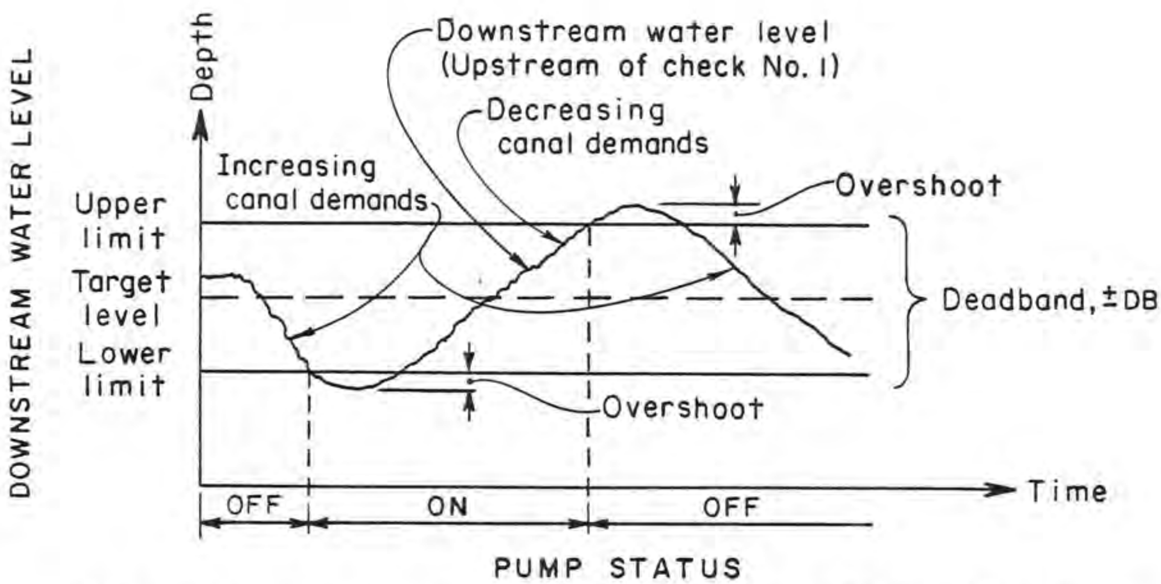

FIGURE 2-ON-OFF, TWO POSITION DOWNSTREAM CONTROL OF CANAL HEADWORKS PUMPING PLANT

The deadband, ±DB measured from the target level, is an essential part of the ON-OFF mode of control. The pump status is ON when the water level is below the lower limit of the deadband and remains ON until the water level rises above the upper limit at which time the pump unit will turn off. The pump unit remains OFF until the water level drops to the lower limit of the deadband.

Additional deadbands can be added to include the automatic start and stop of additional pumping units. The additional deadbands would sense larger variations in the water level from the target level which are associated to larger changes in flow demand at check

No. 1. The additional deadbands (±DB), referred to as "multistages," expand the capability of the canal headworks pumping plant to balance the downstream demand to the canal inlet supply automatically. The multistage, ON-OFF, two-position control is illustrated in figure 3.

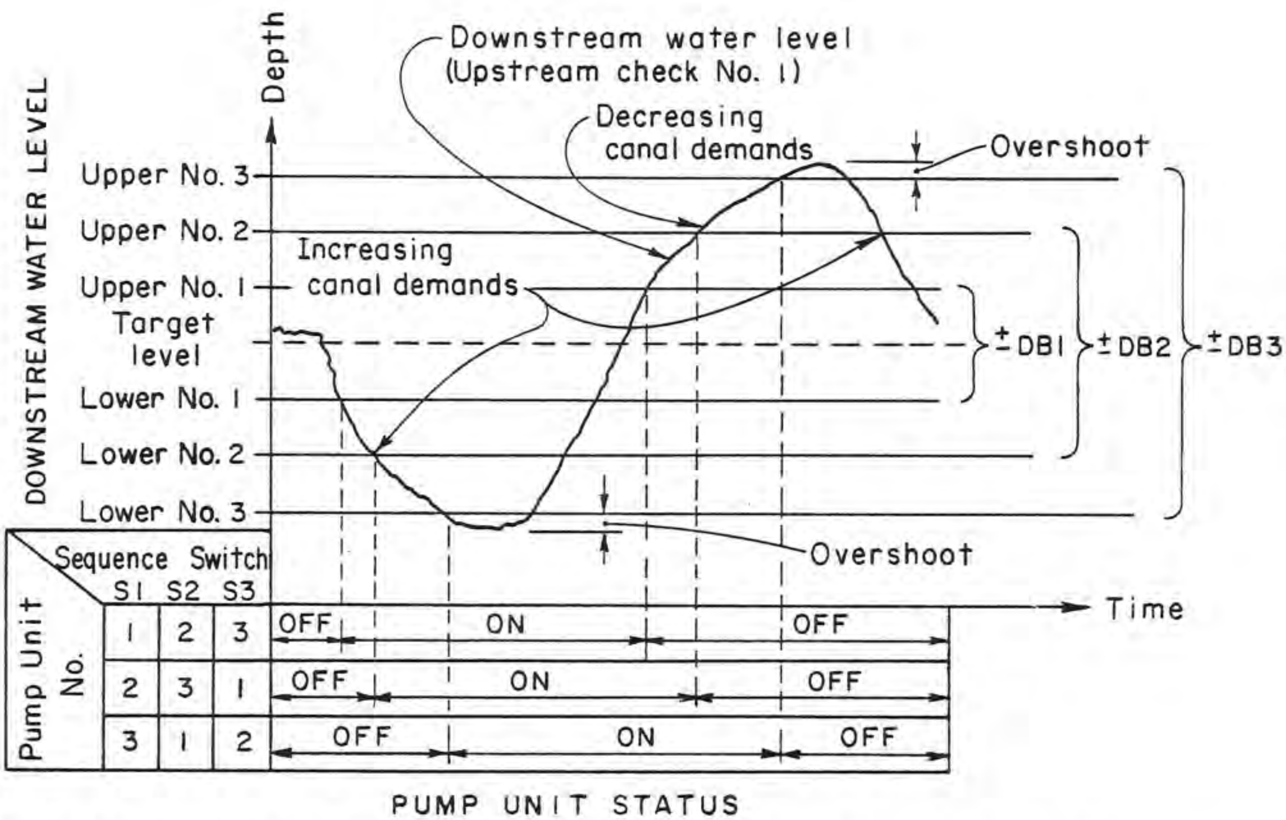

FIGURE 3-MULTISTAGE, ON-OFF, TWO POSITION DOWNSTREAM CONTROL OF CANAL HEADWORKS PUMPING PLANT

Figure 3 shows a multistage ON-OFF control for three pumping units with three deadbands, ±DB1, ±DB2, and ±DB3. Each deadband may be assigned to a particular pumping unit as shown. However, the pump unit with the smallest deadband would have the highest frequency of pump starts. The pump unit with the widest deadband would probably accumulate the longest run time. Most pumping plant operators like to maintain the number of starts and the run time between the pump units nearly equal in order to schedule maintenance of the pump units. A sequence selector switch can be installed to alternate the starting sequence of the pump units such as 1-2-3, 2-3-1, and 3-1-2 as shown in figure 3. Therefore, the starting sequence can be rotated periodically at a schedule established by the operator. The operator can also have the capability to select which units he wants to have operating in the automatic mode and which deadbands he wants to use. For example, if the pump unit sequence was in position S1, figure 3 and he only wanted unit 3 to operate automatically, he would switch units 1 and 2 to the OFF or LOCAL position at the pump unit control boards and leave unit 3 in the AUTOMATIC mode. If the operator wanted to use the smallest deadband instead of the widest deadband and still only use unit 3 for automatic operation, he would change the pump unit sequence switch to the S3 position. Therefore, the operator has a great deal of flexibility for operation and scheduling maintenance programs when the pump sequence switch is incorporated into the multistage ON-OFF automatic downstream control system.

The proper selection of the deadband for ON-OFF control is very important. Small deadbands increase the sensitivity of control action; i.e., the pump units will have a higher frequency of starts and stops which increase maintenance costs. Deadbands that are too small may cause instability. Instability results when the amplitude of the surge wave, caused by a pump unit turning on or off, is greater than the deadband. The pump unit would continuously cycle on and off as the water level passed through the lower and upper limits of a deadband that was selected too small. The continuous cycle, having a period equal to twice the time for a transient wave to travel between the canal headworks and the water level sensor downstream, is a very undesirable flow operating condition and should be avoided.

The minimum desirable deadband can be calculated in terms of an elementary wave traveling downstream in a trapezoidal channel, considering attenuation and reflected surge front, as it arrives at the first check gate [4]. The elementary wave at the headworks when the pump unit starts can be determined as follows:

$$\Delta Yo = \frac{\Delta Q}{T_{ave} \, (\overline{V} + C)} \qquad (1)$$

where: ΔYo = The initial change in water level depth
ΔQ = The pump unit change in discharge
T_{ave} = The top width of the water surface
$\overline{V}$ = The average channel velocity
C = The wave celerity equal to the $\sqrt{g \frac{A}{T}}$ where A equals the cross-section area of flow and g is the acceleration of gravity

The surge wave height as it travels down the canal reach is attenuated [4]. The attenuation factor, AT, is given by:

$$AT = e^{-K(n)gVt} \qquad (2)$$

where:
AT = The attenuation factor at a subsequent time
e = 2.72
K(n) = $[n^2]*R^{-4/3}$ where n is Manning's friction coefficient and R is the hydraulic radius of the channel
g = Acceleration of gravity
V = Velocity of the channel cross section
t = The travel time interval (or dead time) and can be found by t = L/(V+C) where L is the distance the surge wave traverses from the headworks downstream to the water level sensor

When the surge wave arrives at the downstream gate, the surge front will be reflected. If the check gate is partially open, the change in discharge across the surge front will be reduced by an amount equal to the change in discharge under the check gate [4]. However, if the check gate is nearly closed, the surge front is reduced by a small amount. To determine the minimum deadband for the ON-OFF controller, it is assumed the surge wave front will reflect at the check gate when it is nearly closed and be similar to a dead-end barrier having a reflection coefficient equal to 1 [5]. The total change in the surge wave height at the water level sensor after the surge is reflected, in terms of the height of the incident surge arriving from upstream, would, therefore, increase by a factor of 2.

The minimum deadband width, DB(measured from the lower to the upper limit), is calculated by multiplying equations (1) and (2) and multiplying by the reflected wave height factor of 2 as follows:

$$DB_{min} = \Delta Y_0 * AT * 2.0 \qquad (3)$$

If the deadband is measured from the target level and is equal distance above and below, the total deadband width is divided by 2 to get the ±DB shown in figure 2.

Using the Coalinga canal as an example where:

The ΔQ pump unit discharge is 1.3 m^3/s (45 ft^3/s)
The initial low flow condition is 2.6 m^3/s (90 ft^3/s)
The average depth is 3.4 m (11.15 ft)
The bottom width is 3.7 m (12.0)
The side slopes are 1.5:1
The Manning's n is 0.017
The first reach has a length of 2.2 km (7169 ft)

The minimum deadband measured from the target level was determined to be ±20 mm (±0.07 ft).

Wider deadbands will reduce the ON-OFF cycling of the pump units. However, in a typical canal reach there are limitations. The selection of the upper limit, figures 2 and 3, is limited by the height of canal lining and/or the overflow spill crests above the target water level. The minimum height of lining and/or the spill crests will determine the minimum available freeboard for operation of the ON-OFF controller upper limits. The Coalinga Canal check structures have sidebay overflow spill crests on each side of the gate, figure 4. The sidebay overflow allows water to be spilled into the next downstream canal reach if the water level upstream rises more than 60 mm (0.2 ft). Stoplogs, 200 mm (8 in) in height, were added to the Coalinga Canal check No. 1 sidebays to provide a total operating freeboard of 260 mm (0.87 ft) above the target level for the ON-OFF controller upper limits.

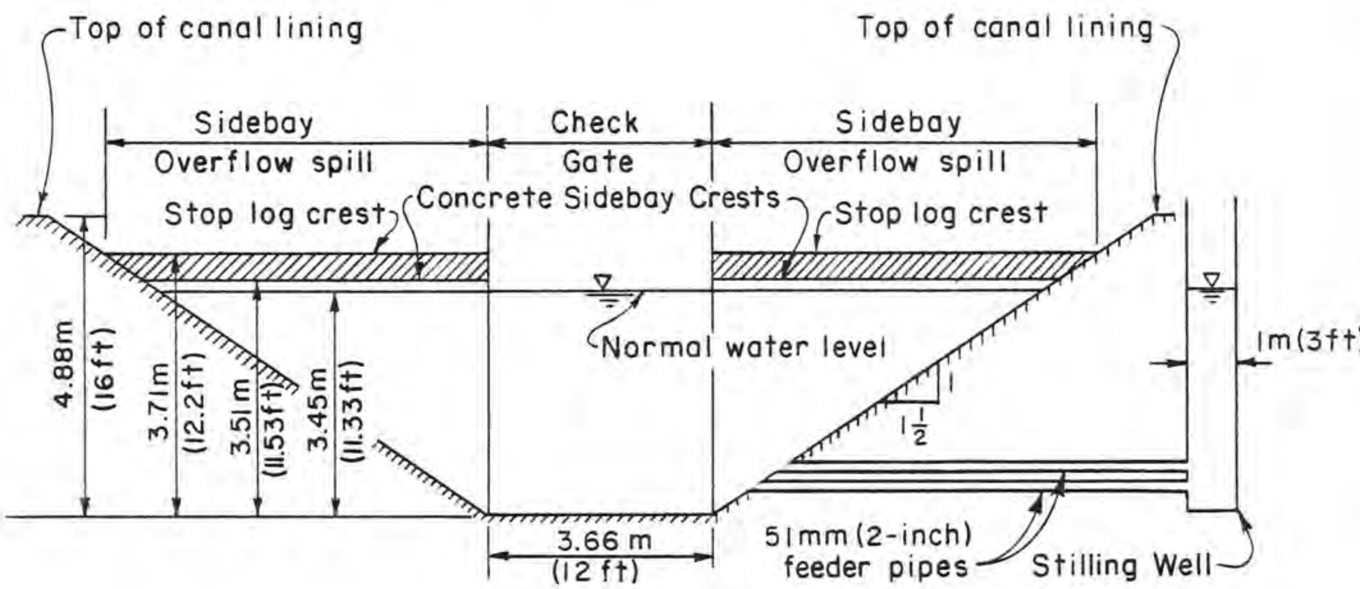

FIGURE 4-COALINGA CANAL CROSS-SECTION PROPERTIES UPSTREAM OF CHECK NO. 1

The lower limit must not be set too low. Low water levels could reduce the flow capacity to canalside turnouts in the first reach. Wide deadbands will result in the canal water level fluctuating over a wide range, between the upper and lower limits including the overshoots, and could cause variable flow discharges into sensitive gravity-type canalside turnouts affecting service to the water user.

The minimum deadband can be estimated using equation (3). However, the selection of the maximum deadband width is largely left to the judgment of the Irrigation Systems Engineer. Before selecting the widths or the upper and lower limits of the second and third deadbands, DB2 and DB3, the maximum overshoot must be estimated, figure 3. The overshoot occurs during the period of time when the transient wave is traveling downstream from the canal headworks to the water level sensor. The period of time is usually referred to as the "dead time" of the canal reach. During the dead time, the water level continues to change after passing through the deadband limit until the resulting control action (starting or stopping a pump unit causing a change of flow at the canal headworks) arrives at the water level sensor and the water level begins to recover. The magnitude of the water level change beyond the deadband limit and before recovery is called the overshoot. The overshoot can be estimated by multiplying the change of flow ΔQ at check No. 1 by the dead time, t, and dividing by the average top width, T_{ave}, and length, L, of the canal reach as follows:

$$\text{OVERSHOOT} = \frac{\Delta Q * t}{T_{ave} * L} \tag{4}$$

To obtain a maximum overshoot for selecting the minimum width of the next wider deadband, assume the maximum change of flow (or mismatch) at check No. 1 is constant and equal to the flow capacity of the pump unit associated with the smaller deadband. Using the Coalinga Canal as an example, with the values of the top width, deadtime, and length used in equations (1) and (2) above and a pump unit flow capacity of 1.3 m^3/s (45 ft^3/s), the maximum overshoot is estimated to be 20 mm (0.07 ft). Equation (4) is the same as equation (1) since t/L equals $1/(\overline{V}+C)$. When the ΔQ's are the same, either equation could be used to approximate the maximum overshoot.

Therefore, the second deadband, ±DB2, of the multistage, ON-OFF, two-position control mode must be at least the width of the first deadband, ±DB1, plus the estimated overshoot magnitude. The third deadband, ±DB3, must be at least the width of the second deadband, ±DB2, plus the overshoot, etc.

For the Coalinga Canal the smallest deadband, ±DB1, was selected at ±50 mm (±0.15 ft) (measured from the target level) as compared to the minimum value of ±20 mm (±0.07 ft) calculated from equation (3). The second deadband, ±DB2, was selected at ±100 mm (±0.33 ft) as compared to the ±70 mm (±0.22 ft) minimum when the estimated ±20 mm (±0.07 ft) maximum overshoot calculated from equation (4) is added to the first deadband, ±DB1, of ±50 mm (±0.15 ft). The third deadband, ±DB3, was selected at ±150 mm (±0.50 ft).

Another factor that should be examined is the frequency of the ON-OFF control pump unit starts that can be anticipated with the smallest deadband, ±DB1. The highest frequency of starts and stops will occur when there is a mismatch of one-half the capacity of the pump unit discharge assigned to the smallest deadband. Using the Coalinga Canal headworks Pleasant Valley Pumping Plant as an example, the mismatch would be 0.65 m^3/s (27.5 ft^3/s) or one-half of the 1.3 m^3/s (45 ft^3/s) small pump unit capacity. The procedure is to add the estimated overshoot, 20 mm (0.07 ft) to the selected narrow total deadband width, DB1, 90 mm (0.30 ft) and then subtract the estimated change in surge wave height, 40 mm (0.14 ft) derived from equation (3). The result, 70 mm (0.23 ft), will be the water level change remaining before the opposite limit, lower or upper, of the narrow deadband is reached and the pump unit of the ON-OFF control mode starts or stops depending if the mismatch 0.65 m^3/s (27.5 ft^3/s) assumed above is negative or positive. The time required for the next pump control action can be estimated by computing the storage volume available in the top 70 mm (0.23 ft) of the canal prism and dividing by the assumed mismatch of 0.65 m^3/s (27.5 ft^3/s). Using the average top width, T_{ave} of 14 m (45.5 ft) and the length, L, of 2.2 km (7169 ft) used in equation (3) and adding the deadtime, t, the total time for the next pump control action would be about 1 hour. Therefore, the frequency of pump units starts would be once every 2 hours. The mathematical model simulating the same flow mismatch showed the highest frequency to be about one pump start every 2.5 hours. A pump unit start every 2 hours was not considered to be unreasonable for the small units. However, for large pumping units, the pump starts in many cases are limited to one per day and could not be used for ON-OFF control with a narrow deadband.

A mathematical model simulating the first canal reach and check 1 gate structure, including the ON-OFF control system of the canal headworks pumping plant, provides the most reliable method for qualitative investigation for selecting the deadband widths. The above approach for estimating the minimum and maximum deadbands can be used to start the mathematical model studies. If a mathematical model is not available, the same approach for sizing the deadbands can be used. Verification should be accomplished by an adequate field trial and error test program. The results of the mathematical model study should also be verified by field tests. By using a mathematical simulation, the number of field test runs would be greatly reduced. Only one or two typical flow changes at check No. 1 would be needed to verify the accuracy of the mathematical model.

It is important to mention that wind wave action on the water surface in a canal prism can cause unnecessary pump control responses if adequate damping or filtering is not provided. Wind waves can easily reach amplitudes of 0.3 m (1 ft) with the winds of 65 km/h (40 mi/h). Wind waves of the 0.3 m (1 ft) magnitude could exceed the limits of the deadband (±50 mm (±0.15 ft) for example) and cause a high frequency of pump unit starts and stops, a very undesirable operating condition, if a properly designed filter, hydraulic or electronic, is not provided. The design of filters for wind wave action or to compensate for the deadtime of the canal reach are not discussed in this paper but are covered in literature cited [1] [2] [4] [6] [8]. However, the P+PR control mode uses an electronic filter to compensate for the deadtime of the first canal reach. The output of the P+PR electronic filter provides the damped or filtered canal water level input to the ON-OFF control mode when the two control modes are combined for automatic operation of the Coalinga Canal PVPP headorks pumping plant. The use of the electronic filter in the P+PR control mode provides adequate damping of the wind wave action and will be discussed further in subsequent paragraphs.

THE P+PR CONTROL

The P+PR control mode has been applied to the automatic downstream control of canal check gates using the controller known as the EL-FLO [2]. The EL-FLO controller using the same basic principles for automatic downstream control of canal check gates can be used for the automatic downstream control of the canal headworks pumping plant if the control parameters are properly selected to achieve a desirable pumping plant automatic operation. It is first necessary to briefly discuss the general theory of the P+PR control as it applies to automatic downstream control of the headworks pumping plant.

The elements of the P+PR automatic downstream control of the canal headworks pumping plant are shown in the block diagram, figure 7 (page 19). The first element is the sensor that measures the canal water surface in the stilling well located at the downstream end of the first canal reach. The output signal, YWELL, of the stilling well water level sensor is modified by the filter element to compensate for the dead time of the canal reach. In the EL-FLO controller the filter is electronic. The water level sensor output is delayed by the electronic filter to produce a phase lag between the response of the total flow change within the period of potential oscillation of the hydraulic transient traveling between the pumping plant and check No. 1. The selection of the filter time constant governs the stability of the P+PR control system by filtering out critical frequencies of disturbances which tend to be amplified by the controller.

The simplest low-pass filter consists of a resistor, R, and a capacitor element, C; in electronic terms, an RC filter. The necessary time constants vary in the range of 100 to 4,000 seconds and are largely dependent on the length of the canal reach downstream. The large time constants can be obtained using electrical components, consisting of FET (field effect transistor) input operational amplifiers, special low leakage capacitors, and sealed resistors, all packaged in a hermetically sealed enclosure, so that the high impedence circuit is shielded from the influence of environmental humidity [1] [2].

The output signal, YF, of the electronic filter is transmitted upstream to the canal headworks pumping plant. The received signal, YF, is the input to the proportional P-controller which solves the equation:

$$QP = K1 * (YT - YF) \tag{5}$$

where:
- QP = Desired P-controller pump discharge
- K1 = The proportional gain constant
- YT = The selected target water level
- YF = The canal water level modified by the filter element

The output of the P-controller, QP, is the input to the proportional reset PR-controller and solves the equation:

$$QE = K2 * \int_0^t (QP \pm RDB)dt \tag{6}$$

where:
- QR = The desired PR controller pump discharge
- K2 = The proportional reset gain constant, per second
- t = Real time, seconds
- ±RDB = The required deadband of the PR-controller

The amount of "offset" (YT-YF), when multiplied by the P-controller gain, K1, determines the demand of flow occurring at check No. 1 and is the desired flow, QP, required at the headworks to balance the demand to the supply. The downstream control concept requires that a decrease in the downstream water surface elevation (modified by a filter) produce an increase of flow at the canal headworks pumping plant to increase the flow into the downstream canal reach. Likewise, an increase in the water surface elevation decreases the flow into the downstream canal reach. Changes in canal flow arriving at a check No. 1 from downstream are, therefore, automatically transferred upstream.

The "offset" is an essential part of the proportional mode, P-controller, and provides a smooth and continuous control action because of the coupling between the controlled variable, downstream flow demand and the pump inflow, upstream supply. The residual "offset" characteristics of the P-controller are gradually eliminated by the PR-controller as time progresses. The PR-controller sums the area of the P-controller output, QR, with respect to time. The accumulated area is multiplied by the PR-controller gain, K2, to obtain an additional desired flow, QR, of the pumping plant.

The P-controller provides the primary control response after a flow change occurs at check No. 1. As a new steady-state flow condition develops at the target depth, YT, the PR-controller provides the primary control response. Typical response is shown, figure 5, of the P+PR automatic downstream control to a sudden increase of canal flow at check No. 1. The PR-controller does not sum the area within the PR-controller deadband, ±RDB. It should be noted how the electronic filter responds during the transient state. During steady-state flow conditions, the electronic filter output, YF, is the same as the canal water level, YC. In the case of the Coalinga Canal, the time contstant of the electronic filter was selected at 1000 seconds. The effects of wind waves of high frequency are filtered out with a time constant of 100 seconds or more and, therefore, are not a problem for the P+PR controller. Since the same filter output, YF, will be used for the input to the ON-OFF controller, figure 7, wind waves will not cause problems for the ON-OFF control mode either.

The output signals, QP and QR, figure 7, of the P and PR controllers are input signals to the comparator unit. The comparator unit sums algebraically the input signals, QP and QR, to obtain the total desired pumping plant discharge, QD, as follows:

$$QD = QP + QR \tag{7}$$

If the total desired pumping unit discharge, QD, exceeds a selected threshold, the first pumping unit is turned ON, figure 6. If more than one unit is automatically controlled, the second unit is turned ON when the total desired pumping unit discharge, QD, is greater than the sum of first unit flow capacity and a second selected threshold,

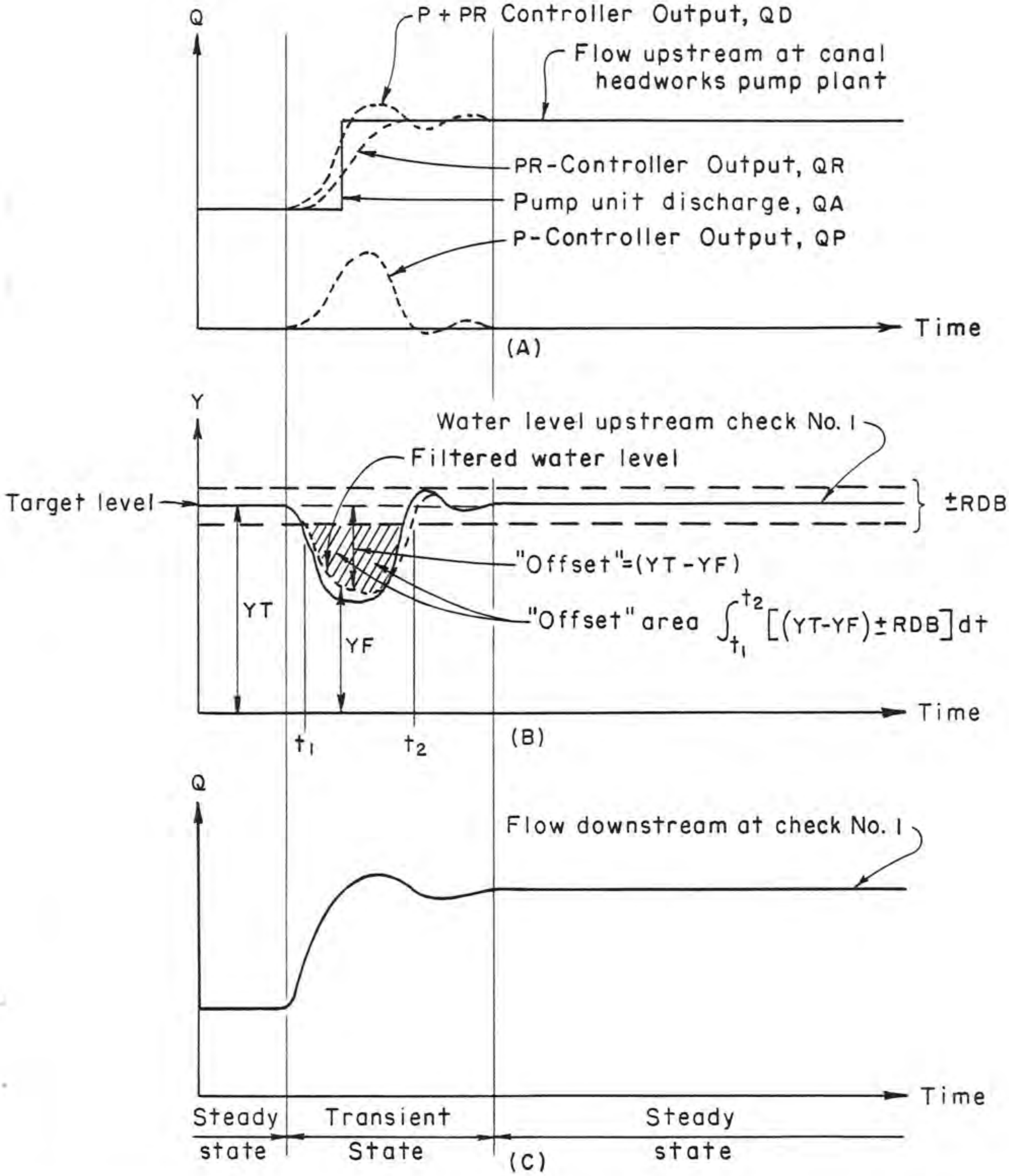

FIGURE 5-TYPICAL RESPONSE OF THE P + PR AUTOMATIC DOWNSTREAM CONTROL OF THE CANAL HEADWORKS PUMPING PLANT TO A SUDDEN INCREASE OF FLOW AT CHECK NO. 1 DOWNSTREAM

etc. The reverse occurs as the computed desired discharge, QD, decreases or when the demand at check No. 1 is less than the headworks pumping plant discharge. When the desired discharge, QD, is zero, indicating the demands downstream are zero, all the automatic pumps are turned OFF.

Comparison studies were made of the ON-OFF control versus the P+PR control of the three small 1.3 m^3/s (45 ft^3/s) pumping units using the mathematical model simulating the Coalinga Canal headworks named Pleasant Valley Pumping Plant and the Coalinga Canal system. The results of the mathematical model comparison study showed the ON-OFF control will average about 20 percent fewer pumping unit starts than the P+PR control with similar water level responses upstream from check No. 1. The 20-percent reduction of pumping unit starts was the main reason for selecting the ON-OFF control mode for the three small pumping units. However, the mathematic model studies indicated the P+PR control mode will provide better water level response characteristics above check No. 1 (compared to ON-OFF control) if the next three larger units were automatically controlled from the downstream water level. It was, therefore, concluded the ON-OFF control mode would control the three small 1.3 m^3/s (45 ft^3/s) pump units and the P+PR control mode would control the next larger three 3.5 m^3/s (125 ft^3/s) pump units, as a result of the mathematical studies.

Central to the stable operation of the P+PR automatic downstream control system is the proper selection of the three primary control parameters (1) the filter time constant, (2) the water level "offset," (YT-YF) magnitude, and (3) the proportionality factor or "gains" K1 and K2. These parameters are selected to eliminate instability, provide the fastest response and recovery of the system to a new steady state without excessive fluctuations of the canal water levels, and to provide the high degree of control (self-regulation). The three primary control parameters are interdependent and are optimized using mathematical models. Without the availability of the mathematical model the proper selection of the control parameters would be extremely difficult and is not recommended if the P+PR control system is to function over a wide range (100 percent) of canalside demands.

THE COMBINED ON-OFF AND P+PR CONTROL

The design strategy of the combined ON-OFF and P+PR automatic downstream control for the canal headworks pumping plant applies the ON-OFF control mode to the smallest pump units and the P+PR control mode to the next larger sized pump units. The Coalinga Canal

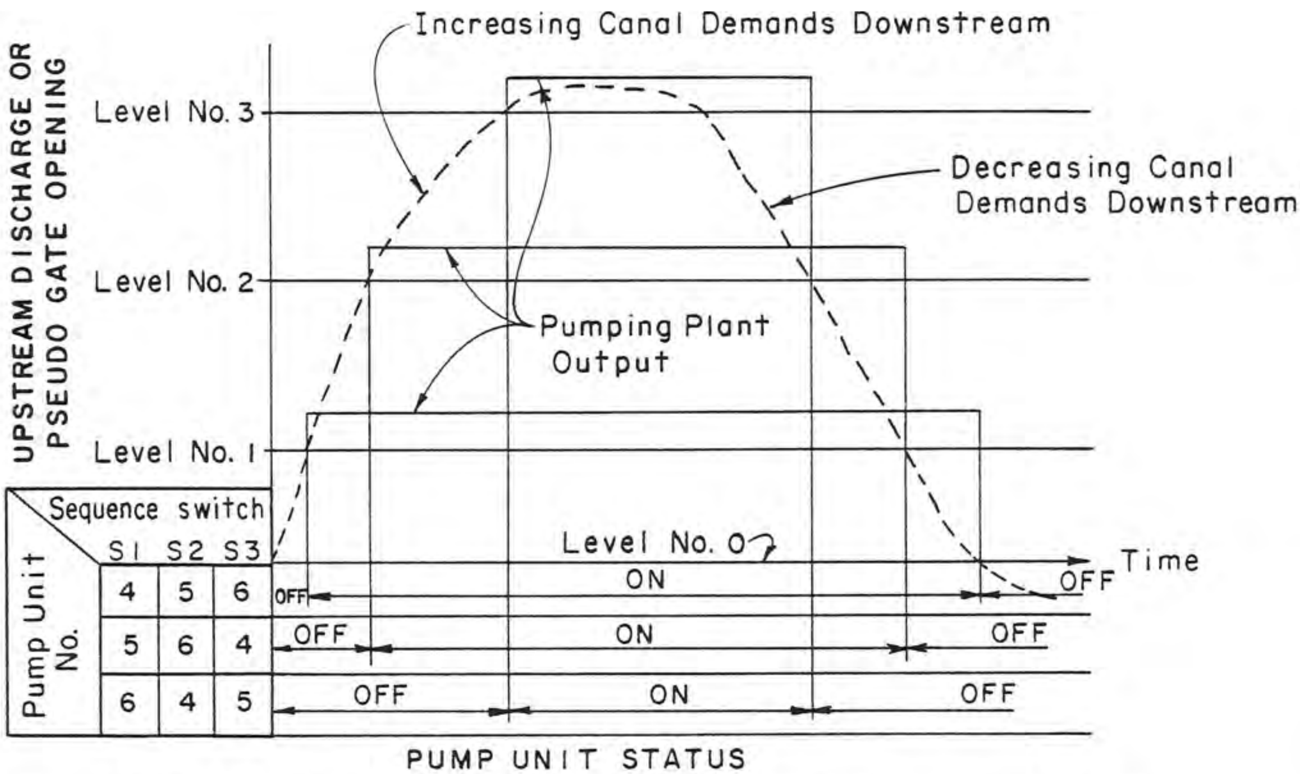

FIGURE 6-P + PR CONTROLLER COMPARATOR UNIT OPERATION OF THE CANAL HEADWORKS PUMPING PLANT

headworks Pleasant Valley Pumping Plant (PVPP)is used as an example. The PVPP has three small pump units having 1.3 m^3/s (45 ft^3/s) capacity each. The next three larger pump units have a discharge capacity of 3.5 m^3/s (125 ft^3/s) each.

The elements of the combined ON-OFF and P+PR control system are shown in the block diagram, figure 7. The first three elements, beginning at the downstream end of the first canal reach, are the water level sensor, filter, and transmitter-communication-receiver, which have been discussed previously. The received filter output, YF, is the input signal to both the ON-OFF and P+PR controllers. The ON-OFF controller consists of a comparator unit. The comparator unit continuously compares the filtered water level, YF, to the referenced inputs which are the selected upper and lower limits of the multistage deadband. When the referenced inputs are exceeded, the actuator of the ON-OFF control mode is energized to start or stop one of the PVPP three small pumping units (as assigned by the pump sequence switch, figure 3) depending on which upper or lower limit has been exceeded.

The P+PR controller, figure 7, uses the same filter, YF, input signal to compute a desired discharge, QD. The general theory of the P-controller, PR-controller, and comparator unit elements has been discussed previously. The comparator unit continuously compares the computed discharge, QD, to the referenced inputs which represent thresholds when the pumps assigned to the P+PR controller are to start as flow demands increase and stop as flow demands decrease. When the referenced inputs are exceeded, the actuator is energized to start or stop one of the next PVPP three larger pumping units (as assigned by the pump sequence switch, figure 6).

The ON-OFF control mode is applied to the PVPP exactly as described previously. However, the P+PR control mode, also described previously, needs further discussion when combined with the ON-OFF control mode.

The P-controller element of the P+PR controller does not have a deadband. It will compute a desired discharge, QP, whenever there is a water level "offset" (YT-YF). However, the P-controller is designed <u>not</u> to compute a discharge that will exceed the total flow capacity of the ON-OFF controllers assigned pumps when the water level is within the widest deadband, ±DB3 of the ON-OFF control mode. The PR-controller does have a deadband, ±RDB, figure 5, and it must be as wide as the widest deadband, ±DB3, of the ON-OFF controller and should include the estimated overshoot ±20 mm (±0.07 ft) previously described. The deadband, ±RDB, would be ±170 mm (±0.57 ft) for the PR-controller when combined with the

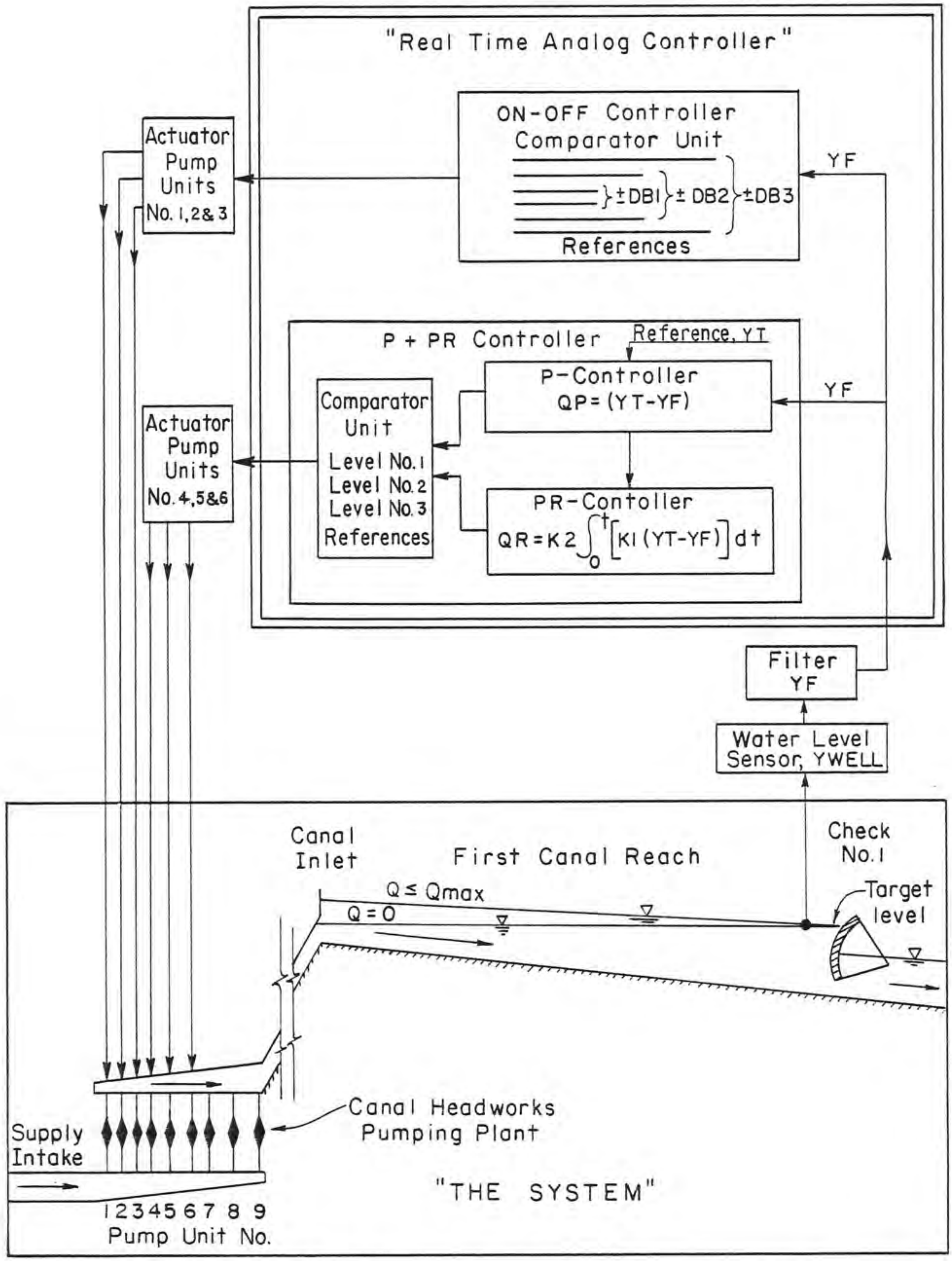

FIGURE 7-THE COMBINED ON-OFF AND P + PR AUTOMATIC DOWNSTREAM CONTROL SYSTEM FOR THE CANAL HEADWORKS PUMPING PLANT

ON-OFF control mode using the Coalinga Canal Pleasant Valley Pumping Plant as an example. Therefore, the P+PR controller is designed not to start or stop its assigned pump units within the flow range of operation of the ON-OFF controller pump units; i.e., the smaller pump units of the ON-OFF controller will automatically start or stop before the next larger pump units of the P+PR controller start or stop. The P+PR controller will compute the flow demands that exceed the flow range of the ON-OFF controller pump units as the desired discharge, QD. The comparator unit of the P+PR controller will energize its actuator to start an assign pump unit when the computed discharge reaches a threshold of about 85 percent of the pump unit discharge capacity as demands increase. The P+PR controller will stop the pump unit when the computed discharge, QD, has decreased by about 115 percent of the pump unit discharge capacity. Figure 6 illustrates how the comparator unit of the P+PR controller functions.

Notice in figure 6 the vertical axis has two scales. The two scales are called the "Upstream Discharge" or "Pseudo Gate Opening." The P+PR controller computes the discharge, QD, in terms of a pseudo gate opening - meters (feet). The comparator unit reference inputs or thresholds are also in terms of the pseudo gate opening. However, the P+PR computed discharge, QD, can actually be in discharge units of m^3/s (ft^3/s) by multiplying by a scaling factor or gain of 5.3 m^3/s per 1 m (56 ft^3/s per foot) pseudo gate opening. The scaling factor could have been incorporated into the P+PR control parameters, K1 and K2, if it was necessary to have the output in actual units of discharge, m^3/s (ft^3/s). However, since the pseudo gate opening and discharge relationship was established linearly, it was not considered necessary to include the scaling factor in the gains, K1 and K2.

The control parameters, K1 and K2, for the P+PR controller when combined with the ON-OFF control mode and applied to the PVPP were selected using the mathematical model of the Coalinga Canal system. The P-controller gain, K1, was selected at 1.5 m/m (1.5 ft/ft), the PR-controller gain, K2, was selected at 0.0010 per second. These K1 and K2 values will compute the desired discharge, QD, in terms of the pseudo gate opening. All measured and computed values in the final prototype ON-OFF and P+PR control system must be properly scaled and calibrated if each element is to perform correctly. A time constant of 1000 seconds was used for the filter element.

THE OPERATION OF THE ON-OFF AND P+PR CONTROL

The time history plot, figure 8, illustrates how the combined control system responds when the downstream demands at check No. 1

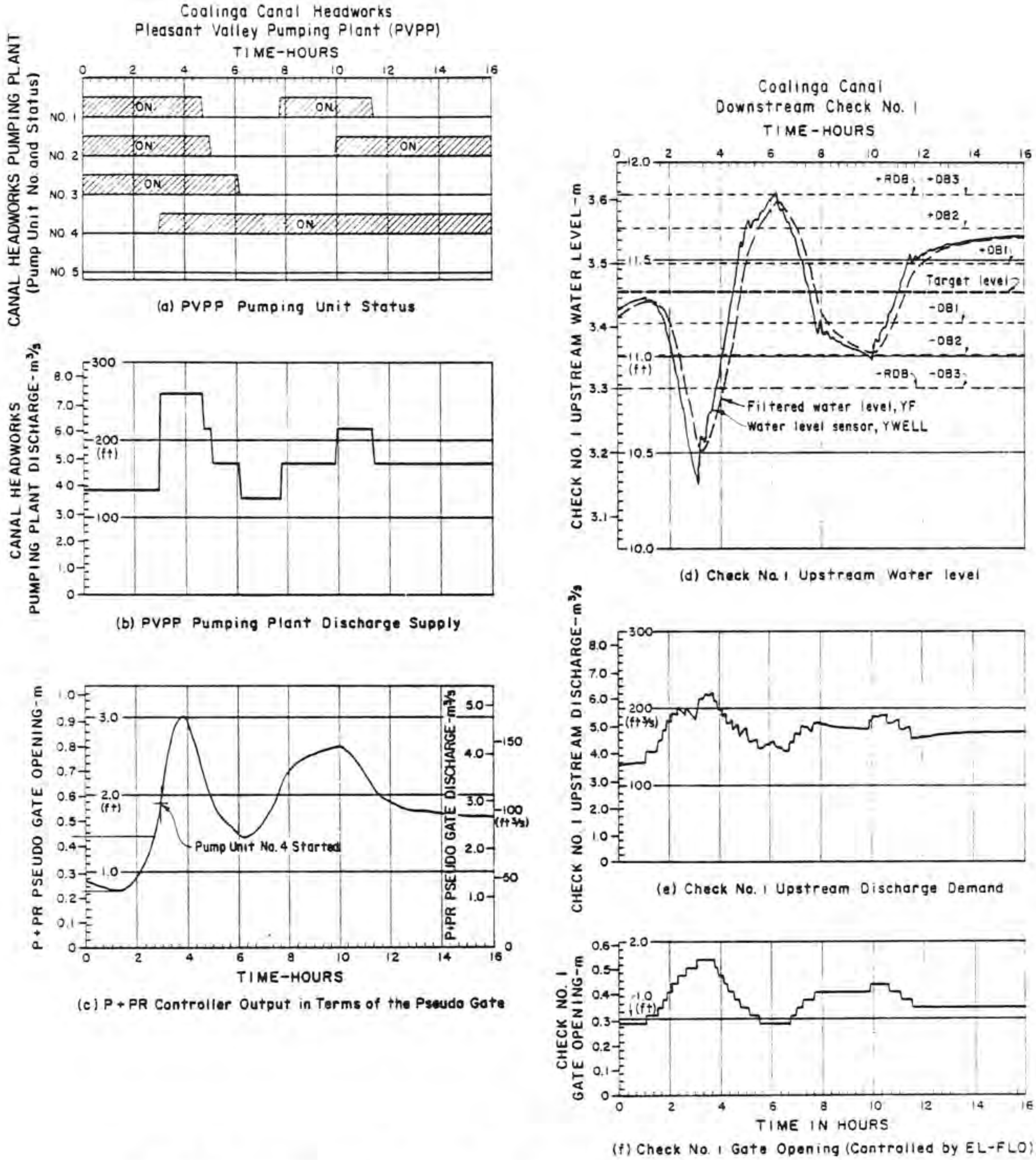

FIGURE 8 - MATHEMATICAL MODEL SIMULATION OF THE COALINGA CANAL HEADWORKS PLEASANT VALLEY PUMPING PLANT (PVPP) AND DOWNSTREAM CHECK NO. 1 WITH THE COMBINED P + PR AUTOMATIC DOWNSTREAM CONTROL ILLUSTRATING THE TIME HISTORY OF THE CONTROLLER PERFORMANCE

increase and exceed the discharge capacity of the ON-OFF control pump units. Figure 8 was taken from the results of a mathematical model computer run simulating the entire Coalinga Canal system. Only the Coalinga Canal headworks Pleasant Valley Pumping Plant, the first canal reach, and the check No. 1 are shown. A steady-state flow condition of 3.6 m^3/s (128 ft^3/s) was established at check No. 1, figure 8e at time zero. The three pump units of the ON-OFF control mode are running and discharging a total inflow of 3.8 m^3/s (135 ft^3/s), figure 8b. At time 0.2 hour the flow through a canalside turnout at the end of the Coalinga Canal, 14.8 km (9.22 mi) downstream, was increased by 1.4 m^3/s (50 ft^3/s) requiring a new steady state total flow of 5.0 m^3/s (178 ft^3/s) which exceeds the pump capacity of the ON-OFF control mode. Check No. 1 gate begins to respond automatically to the increased demand at time 1 hour, figure 8f, using the EL-FLO control system for the Coalinga Canal check gate structures.

Figure 8e shows how the increased demand downstream develops at check No. 1. Figure 8d shows how the water level response to the increased demand and figure 8c is the output of the P+PR control mode in terms of the pseudo gate opening as the demands increase. Figure 8a and 8b show the headworks PVPP pump units status and the discharge into the first canal reach downstream. The P+PR control mode starts its first assigned pump unit No. 4 at time 3 hours increasing the canal inflow by 3.5 m^3/s (125 ft^3/s) to a total of 7.3 m^3/s (260 ft^3/s). The supply now greatly exceeds the demand of 5.0 m^3/s (178 ft^3/s). However, the ON-OFF controller will shut down its units as the water level rises and exceeds the upper limits of the deadbands. As time progresses, the ON-OFF controller establishes a new steady-state inflow of 4.8 m^3/s (170 ft^3/s) at time 11.5 hours and matches the check No. 1 flow demand of 4.8 m^3/s (170 ft^3/s).

Figure 8 illustrates that the P+PR controller will not operate within the flow range of the ON-OFF control mode. Operator attendance was not required at time 3 hours to start the next larger pump unit and stop the smaller pump units to balance the downstream demand to the upstream supply.

A second mathematical model computer run (not included) was made with the same flow conditions to illustrate the importance of having an operator on duty to start pump unit No. 4 at the proper time when operating in the manual mode. In the second run, pump unit No. 4 was manually started at 3.5 hours, 30 minutes after the automatic start had occurred. As a result of the 30-minute delay, the water level upstream of check No. 1 decreased by 0.6 m (2 ft) as compared to the 0.3 m (1 ft) water level drop for the automatic operation, figure 8d. The additional water level drop is a significant amount for only a 30-minute delay. A longer delay may have had an adverse effect on the delivery water to the adjacent canalside turnouts.

There are other important considerations regarding the automatic downsteam control of the canal headworks. The conveyance facilities upstream of the canal headworks will require a certain degree of operational flexibility. If the water supply to the canal headworks is from a regulating reservoir, then the variable flow resulting from the automatic operation of the canal headworks (pumps starting and stopping to maintain an average flow, for example) can be absorbed from the available storage. However, if the supply is from another main canal system, the available storage will be considerably reduced and may limit the amount of variable flows that can occur for an automatic canal headworks' operation. Therefore, the flow characteristics of the source of supply upstream of the canal headworks is an important consideration in the design of an automatic control system.

The source of supply to the canal headworks in many installations requires advance scheduling, usually 24 hours. The average diversion to the canal headworks must agree with the advanced schedules, particularly if the supply is from another main canal system which has minimal storage space available for mismatches. The regulating reservoir that has available storage usually does not require a precise match of the advanced schedule to the diversion. The mismatches that occur one day can be adjusted for in the advanced schedule submitted the next day to maintain the reservoir water surface elevation near the target level.

For many canal headworks that consist of a relift pumping plant, advanced scheduling of water also schedules the required power supply for the number of pumps needed to meet the scheduled demand. Therefore, provisions must be included in an automatic operation of a canal headworks pumping plant to insure that the peak pumping rate does not accidentally exceed the advanced schedules. The provisions required are relatively simple. Each pump unit control board is furnished with an OFF-MANUAL-AUTOMATIC three-position switch. The pump units <u>not</u> required to meet the demand schedule are simply "locked out" to OFF or MANUAL mode. The pump units needed are left in the AUTOMATIC mode. If the canal demands should happen to exceed the advanced orders (when the water users divert more water than they have ordered in advance) additional pump units will not start up. The canal water levels in the canal prism will decrease and activate the low water alarms. The operator is notified and he then takes the necessary corrective action by ordering additional water and power, if possible, on a short notice or have the water users using excess water reduce their diversions until a new schedule can be approved and the water is available at the canal headworks.

If there was a sudden unannounced decrease in demand as a result of a rainstorm or a local power outage at canalside pump turnouts, for example, the supply is automatically reduced at the canal headworks. The decreased pumping would not cause a problem with the power schedules. However, the rejected flow at the canal headworks pumping plant may cause a problem if the supply is from another main canal system. The operators of the main canal supplying water to the canal headworks would have to be notified promptly so they can adjust their canal to reduce the supply upstream. The rejection of flow back into a regulating reservoir would probably not cause any problems.

The Coalinga Canal headworks Pleasant Valley Pumping Plant has three more large pumping units, each having a flow capacity of 6.4 m^3/s (225 ft^3/s). These three largest units will be operated manually. The operator will manually start one of these pump units when the canal demands are expected to exceed the pump unit capacity for a long period of time. There are two ways the operator can put the large unit into operation. He can shut OFF the smaller pump units of the same total capacity first (even if they are running in the AUTOMATIC mode) and then immediately turn the larger pump unit ON. He can also turn the larger unit ON (after the additional power has been scheduled in advance) and simply let the combined ON-OFF and P+PR controller automatically shut down the smaller units if the supply exceeds the demand. In both cases, he will probably turn the larger unit ON to coincide with an increase in canal demands downstream.

The same manual operating procedure, used for an increase in demand, can also be reversed for the decreasing demands. The same operating procedure could also be used for manual operation of the smaller units leaving selected units in the AUTOMATIC mode to accommodate for changes in demand that may occur during off-duty hours. The combined ON-OFF and P+PR control system provides a great deal of operational flexibility for the pumping plant operator.

ADVANTAGES

The combined ON-OFF and P+PR control system provides several significant advantages. Critical pumping plant operator attendance which may be required at any hour of the day is eliminated. The control system provides flexibility of operation. The pumping plant operator will find the P+PR control mode option useful when the canalside demand changes exceed the capacity of the ON-OFF control mode pump units and when the exact timing is difficult to predict or when canalside demand changes are unannounced. The number of pump units starts can be kept to a minimum with the proper selection of controller deadbands and gains. The operator can maintain peak-pumping rates within established water and power supply schedules. A balance between the downstream variable water demands and canal headworks supply can be easily maintained without unreasonable water level variations in the downstream canal reach.

DISADVANTAGES

Without the availability of mathematical simulation of the canal system which requires a large computer system, the selection of P+PR control parameters could not be done successfully. The deadbands of the ON-OFF control mode can be estimated. However, without the aid of the mathematic model, an extensive field test program would be required to verify the selected values to provide the desired operation. The automatic operation of the canal headworks pumping plant may result in more pump starts over a period of time compared to a manual operation. However, the maintenance of canal water levels within desired limits over the same period would probably not be maintained for the manual operation. The supply system to the canal headworks will require a degree of operational flexibility to accommodate the automatic control operation as it responds to variations in canalside demands downstream.

SUMMARY AND CONCLUSIONS

The results of the mathematic model studies has demonstrated that automatic downstream control of the Coalinga Canal Headworks Pleasant Valley Pumping Plant can be successfully achieved with the combined ON-OFF and P+PR control modes. The combined control system will provide the same high degree of control of the headworks pumping plant as has been provided for on the EL-FLO operated canal check gates. Critical operator attendance can be greatly reduced (and eliminated at any particular hour of the day) from three 8-hour shifts to one 8-hour shift providing certain economic benefits.

The economic savings are not the only benefits. Automatic downstream control of the canal headworks completes the coupling of the canalside demands downsteam to the source of supply. The ON-OFF and P+PR control system has flexibility of operation, is alert to demand changes and takes responsible corrective action, and can achieve optimum operational efficiency on a continuous basis. The ON-OFF and P+PR control system has application to other canal headworks relift pumping plants.

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