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Reduction of Minimum Switching Time Error in Second Order Plant Using Non-Linear Binary Controller

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ABSTRACT

In this paper, the non-linear binary controller is used to reduce the minimum switching time error to a zero value which occurs exactly at its two minimum switching times also called the switch transfer and re-transfer times with each comprising system response sensor time and the delay time. The problem with the analysis, design and simulation of the non-linear binary controller is the selection of the right optimal value of the controller gain with reason being that the control signal of controller is a discontinuous function of its input. This work employed some mathematical sophistication involving both the integral calculus and optimal control theory to select the right optimal value of controller gain which is used in the reduction of minimum switching time error from the minimization of its quadratic performance index (QPI). The control signal was programmed on Arduino uno for use as the load tap changer (LTC) control in the drive unit of load tap changing power transformer. The results of five simulations ran showed that non-linear binary controller with contactor as its switching mechanism took 10 milliseconds for a second order plant (small power transformer) having it as its LTC control to react to load voltage changes whereas Digital servo motor controller (DSMC) from the manufacturer's specification took about 2 seconds.

Keywords: Non-linear binary controller, load tap changer control, Digital servo motor controller, quadratic performance index, transfer time, re-transfer time

1. INTRODUCTION

The term controller in a feedback control system is often associated with the elements of the forward path between the actuating (error) signal e and the control variable [1]. There are generally two types of controllers: the linear and non-linear controllers. Examples of linear controllers are P, PI and PID controllers, where each of their outputs is defined by linear operations, or linear combinations of linear operations, on each of their inputs. The non-linear controllers however, have non-linear input-output characteristics. One such non-linear controller is the Binary controller which is clearly a non-linear controller since its output is a discontinuous function of its input. It accepts the actuating signal and delivers a control signal at its output which is a digital signal. PID controller is actually a natural generalization of the non-linear Binary controller [2]. Assuming that the process has a positive static gain, high-level control signal will cause increase in controlled variable also called the system response. The main idea in this way of control, with only two control signal levels is to achieve the desired value of the controlled variable in the minimum time.

The choice for the non-linear binary controller design follows its advantages which are economical, simple to design, does not require any parameter tuning, eliminates minimum switching time error, requires little or no maintenance, achieves faster system response to specific inputs, used with actuators that work in only two modes, and its system operation and performance is not hampered by the oscillations of the controlled variable about their desired input values also called set point [1]. Non-linear binary controllers find applications in numerous control system designs as seen in thermostatically controlled heating systems. This controller regulates the room temperature about the desired room temperature [2]. Electronic switching non-linear binary controllers employing transistors and thyristors are also being used in many modern electric motor drive systems [3, 4].

2. REVIEW OF RELATED LITERATURES

Erham *et al*. designed a new on-off controller based on Arduino uno with application to window air conditioner [5]. To maintain the desired room temperature, the AC employs the thermostat is used to the set point and the temperature differential. However, the differential is not always easy to set. To solve this, he replaced the thermostat of the AC with Arduino based binary controller in which was uploaded algorithm of on-off controller. The results obtained showed that the system response at crucial time points has error with lower range from 0.02 ˚C to 0.38 ˚C unlike the conventionally based thermostat error whose range is higher from 0.5 ˚C to 0.95 ˚C. This gave a more accurate designed controller system response. Moreover, the designed controller reduced the energy consumption by about 66 % compared to the thermostat.

Sichwart proposed the implementation of load tap changer control using key elements of IEC 61850 [6]. These key elements include a merging unit which interfaces with analog signals, and an actuator module. GOOSE messaging is used to achieve the objective of operation with networked communication as against copper cable communication. This option is viable for LTC control because it is not time critical. The scheme offers significant benefits upon full implementation. Such benefits are wiring reduction, flexibility improvement, reduction in number and complexity of necessary devices and interoperability. However, the proposed LTC control scheme produced results that have no fast operations as observed in operation and processing delays that depends entirely on networked communication that offers slower time response for any circuit having the LTC control used by author to react to voltage variations.

3. RESEARCH METHODOLOGY

For this non-linear binary controller, the unity negative feedback control system with linear continuous time invariant second order plant (power transformer P/T) is shown in Figure 1.

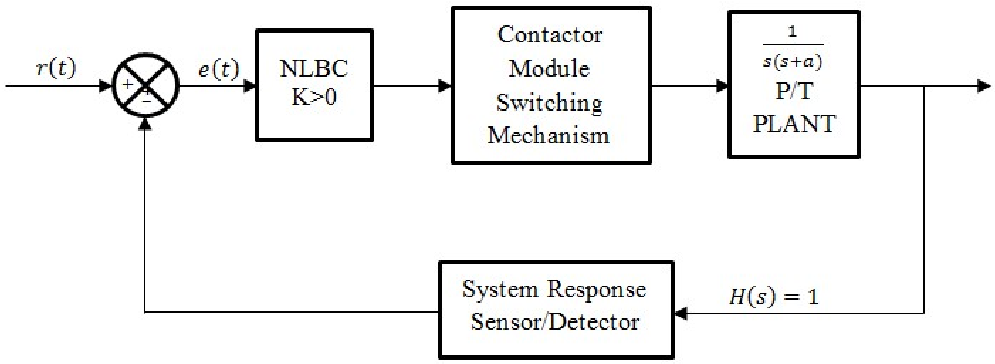

Figure 1: Unity negative feedback control system with non-linear binary controller and plant (small power transformer P/T)

Phase plane methods, a mathematical tool for analyzing second order non-linear systems represented by nonlinear differential equations expressed in state variable form without the need for linearization about their operating points was used in the analysis and design of the non-linear binary controller. This gave two curves after switching in the 2nd and 4th quadrant of the phase plane as its transfer and re-transfer minimum switching times respectively as shown in Figure 2. Also, two curves prior to switching which comes from the location of the initial conditions $x_1(0), x_2(0)$ above or below the switching curve and for which the non-linear binary controller develops the control signal $u = +1$ and $u = -1$ respectively. Obtaining the phase plane trajectory which is a locus in the phase plane parameterized by time which are fractions of its two minimum switching times both given as transfer and re-transfer traversed by the control signal traverses the phase plane trajectory. The non-linear binary controller switches its values from $u = -1$ to $u = +1$ (transfer) or from $u = +1$ to $u = -1$ (re-transfer) to perform either a tap raise or tap lower LTC control operation in order to raise or lower secondary voltage of power transformer back to its nominal value.

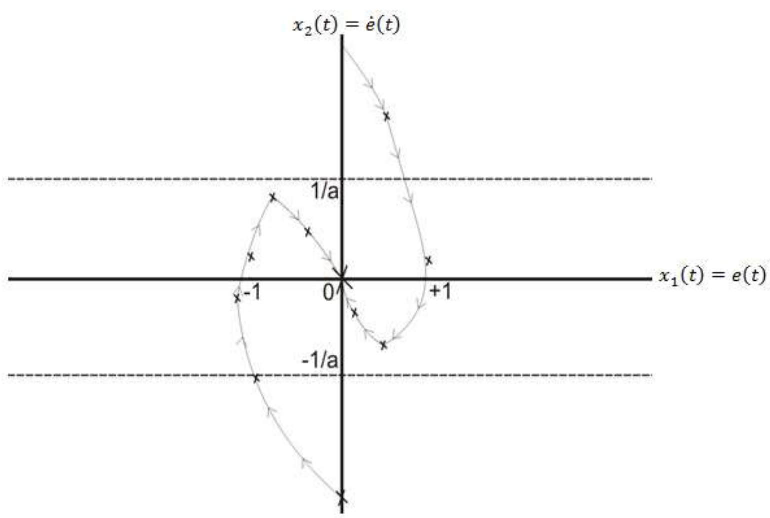

Figure 2: Phase plane trajectory of the non-linear binary controller for $a > 0$

Error analysis gave the system response error which is input to the non-linear binary controller as

$$e(t) = e^{-\alpha t}\sqrt{1+\left(\frac{\alpha}{\beta}\right)^2}\sin\left(\beta t + \tan^{-1}\frac{\beta}{\alpha}\right) \qquad (1)$$

where $\alpha = \frac{a}{2}$, $\beta = \sqrt{K - \frac{a^2}{4}}$ and $K > 0$ is the gain of the non-linear binary controller and $a \geq 0$ is a design parameter of the approximated type one second order plant which in this case is load tap changing power transformer.

Minimization of the quadratic performance index,

$$\text{QPI} = \int_0^\infty e^2(t)\,dt \qquad (2)$$

yielded $K = a^2$ as the right optimal choice of $K > 0$ which was entirely performed using the integral calculus.

With the obtained optimal value of K, the two minimum switching times (transfer and re-transfer times), system stability information, performance specifications - speed of the system response to the unit step function, and relative stability were all determined by purely analytical means. Lastly, the algorithm of the non-linear binary controller was programmed in MATLAB and uploaded into the Arduino uno, and afterwards used as the load tap changer controller in the drive unit of the small power transformer as shown in Figure 3.

T_d expressed as time domain specification is the time required for the unit step system response (controlled variable), i.e., $c(t) = 1 - e(t)$, to reach 50% of its final value, while sensor time is minimum switching time minus delay time.

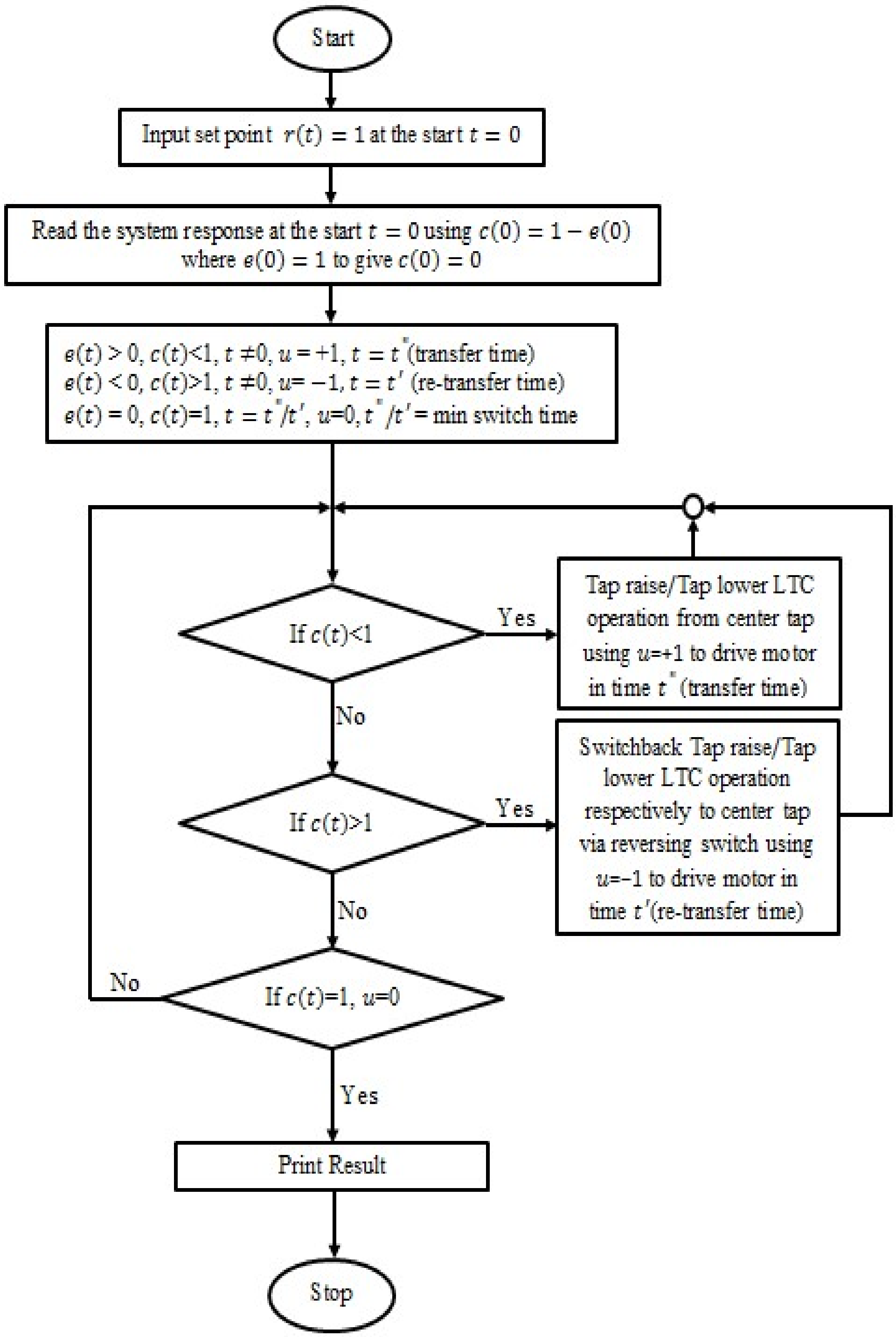

Figure 3: Non-linear binary controller algorithm flowchart

Non-linear binary controller used as the load tap changer control in the drive unit of VI VRLTC vacuum reactance type load tap changer was simulated with the small power transformer (63 MVA, 132/11 kV) where the low voltage side was regulated within $\pm$ 10% with 16 steps or (17 taps). Figure 4 shows the overall system, where SEL-2414 is the power transformer monitor, i.e., a unit step system response (controlled variable) monitor/sensor which serves both as a monitor and merger unit and thus interfaces with analogue signals which is the measured secondary voltage of 11 kV, and afterwards communicated digitally over the Ethernet cable in the form of IEC 61850 GOOSE MESSAGING to the non-linear binary controller as the load tap changer control with contactor module as switching mechanism that implements the control action via control signal $u(t)$.

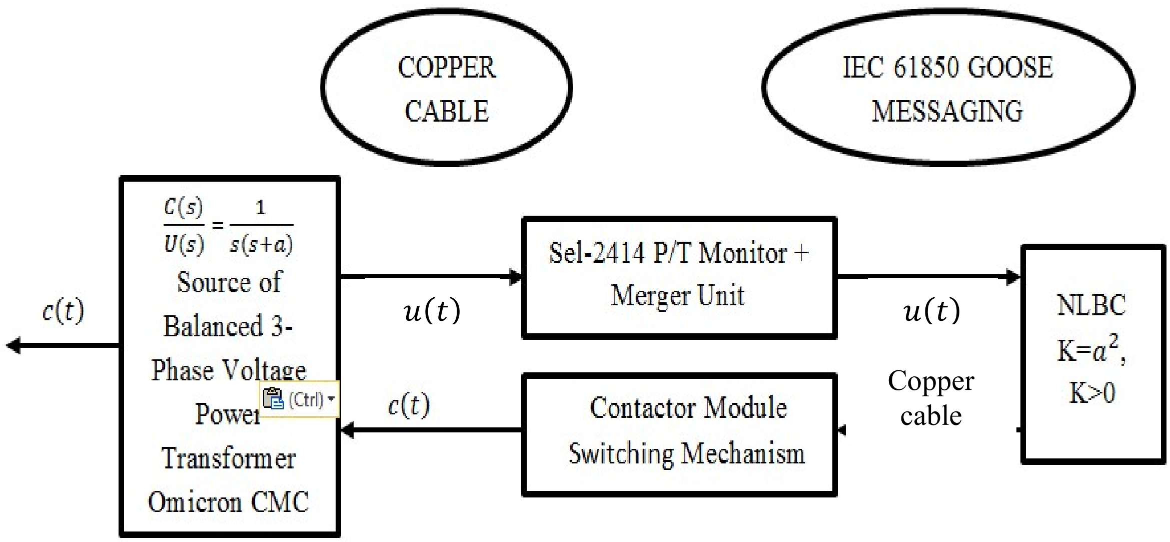

Figure 4: Non-linear binary controller used as load tap changer control overall system operation

4. RESULTS

Using the dead zone property of the non-linear binary controller which is the fact that the system response error $e(t) = 0$ exactly at the two minimum switching times only when $u(t) = 0$, both the transfer and re-transfer times are given as:

t''(transfer minimum switching time) = $-\frac{2\pi}{3a\sqrt{3}} \approx -\frac{1.21}{a}$ seconds (2nd quadrant of the phase plane) and t'(re-transfer minimum switching time) = $\frac{4\pi}{3a\sqrt{3}} \approx \frac{2.42}{a}$ seconds (4th quadrant of phase plane) where $a > 0$ is the design parameter of the second order plant (tap changing power transformer). For the non-linear binary controller used as load tap changer control with contactor module, i.e., heavy duty electro-mechanical relay as switching mechanism, $a > 0$ is in the range: $1 \leq a < 200$. For this work, $a = 120$, thus, t''(transfer) = 10 milli-seconds and t'(re-transfer) = 20 milli-seconds.

Digital Servo Motor Controller (DSMC), a load tap changer control in vacuum interrupter Reactance Type load tap changer (VRLTC) is the case study under investigation. From manufacturer's specification as revealed in the physical characteristics of VRLTC-1500/25, its tap changer speed is less than 2 seconds [7] while the minimum switching time (transfer time) of non-linear binary controller is 10 milli-seconds. Table 1 shows a comparison of the switching mechanism and times of DSMC of VRLTC-1500/25 with the non-linear binary controller (NLBC) for a 50Hz AC voltage and with plant parameter $a = 120$.

Table 1: Comparison of the switching mechanism and times of the DSMC of VRLTC- 1500/25 NLBC for a 50Hz AC voltage with plant parameter $a = 120$

Name	Switch Type	Switching Mechanism	Transfer Time	Detection Transfer Time	Delay Transfer Time	Re-Transfer Time	Source
DSMC	CTTS	Contactor	< 2 sec	< 1 sec	1 sec	-	ABB Inc (2011)
NLBC	CTTS	Contactor	10 ms	3 ms	7 ms	20 ms	This Study

After running five simulations for Tap Raise LTC control operations of a VRLTC-1500/25, the results are shown in Table 2 with the centre tap position 9 having the measured secondary voltage of 6.35kV and 1000 turns as the number of primary turns. The table also shows the reduced number of primary turns, raised voltage due to a fall below secondary voltage, transfer time and the number of Tap Raise LTC operations from center tap position 9 needed to boost voltage back to its nominal value.

Table 2: Summary of tap raise LTC operation simulation results

Simulation	$V_2' < V_2$ kV rms	Tap Position Selected	Reduced Primary Turns	Raised voltage kV rms	Transfer Time t'' in milli-secs	Number of Tap Raise LTC
1	6.24	10	988	6.43	10	1
2	6.15	11	975	6.51	10	2
3	5.84	15	925	6.87	10	6
4	5.77	16	913	6.96	10	7
5	5.72	17	900	7.06	10	8

Similarly, after running five simulations for the tap lower LTC control operations, the results are shown in Table 3 with the centre tap position 9 having the rated measured secondary voltage of 6.35kV and 1000 turns as the number of primary turns. The table also shows the increased number of primary turns, lowered voltage due to a rise above the rated secondary voltage, transfer time and the number of tap lower LTC operations from center tap position 9 needed to buck voltage back to its nominal value. The results of both tap raise and tap lower LTC control operation simulation are reliable in keeping a constant low side voltage of transformer.

Table 3: Summary of tap lower LTC operation simulation results

Simulation	$V'_2 > V_2$ kV rms	Tap Position Selected	Increased Primary Turns	Bucked voltage kV rms	Transfer Time t'' in milli-secs	Number of Tap Lower LTC
1	6.48	8	1013	6.27	10	1
2	6.54	7	1025	6.20	10	2
3	6.75	4	1063	5.98	10	5
4	6.89	3	1075	5.91	10	6
5	6.95	2	1088	5.84	10	7

5. CONCLUSION

Non-linear binary controller reduces minimum switching time error. This follows directly from its highly optimized gain $K > 0$ which is from optimized quadratic performance index with the result of very fast switching speed non-linear binary controller. This is revealed in its two minimum switching times only for very large design values $a > 0$ of the chosen 2nd order process. The load tap changing small power transformer was controlled with the non-linear binary controller. Sampled values messaging was used to transmit voltage measurements to the LTC control as well as to advance the control logic to accommodate more realistic operating conditions such as triggering LTC operation according to predicted load flow or blocking of the LTC control also called "Locking out of LTC" during faults, malfunctions or impending failure of the drive system or the LTC components.

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