Load Tap Changing Control

J. H. Harlow
Consultant to Beckwith Electric Company
6190-118th Ave. North, Largo, FL 34643-3724, USA

ABSTRACT

The control used for the tapchanger of an LTC transformer or step-voltage regulator is a prime illustration of electronic technology advances applied to the power industry. Electro-mechanical (balance-beam and induction disc), discrete static, integrated circuit static and now digital designs have evolved over the past forty years. This increased product sophistication has made possible many features beyond the primary objective of simple raise-lower commands in response to the measured secondary voltage.

BASIC CONTROL

This very basic LTC control, as routinely provided and as required by IEEE/ANSI standards, requires five basic setpoints. Three of these are used with every installation.

Voltage Level (bandcenter)

This is the voltage, spoken in terms of the 120 V basis of the control, which is desired to be held at the load. The load will usually be removed from the transformer, in which case the electrical distance to the load is defined by the line drop compensation settings. Simplistically, if LDC (see below) is set to zero, the voltage level is the output voltage of the LTC transformer. It is commonly required that the voltage at the load be held in the range of 114 V to 126 V although particular utilities may impose far more stringent criteria.

Voltage Bandwidth

Due to the voltage step change nature of the LTC output, there must be some range of voltage about the voltage level setting which is acceptable to the control and will be recognized by the control as being “in-band.„ Thus, the bandwidth, also expressed in volts on the 120 V base is the total voltage range, one-half of which is allowed above, and one-half below the voltage level setting. There is always a minimum acceptable bandwidth setting, usually considered to be twice the voltage change per LTC step change, or 1.5 volts in the common system. In fact, 2.0 and 2.5 volts are the most common settings with 3.0 V and higher values being used where tight regulation is not required.

Time Delay

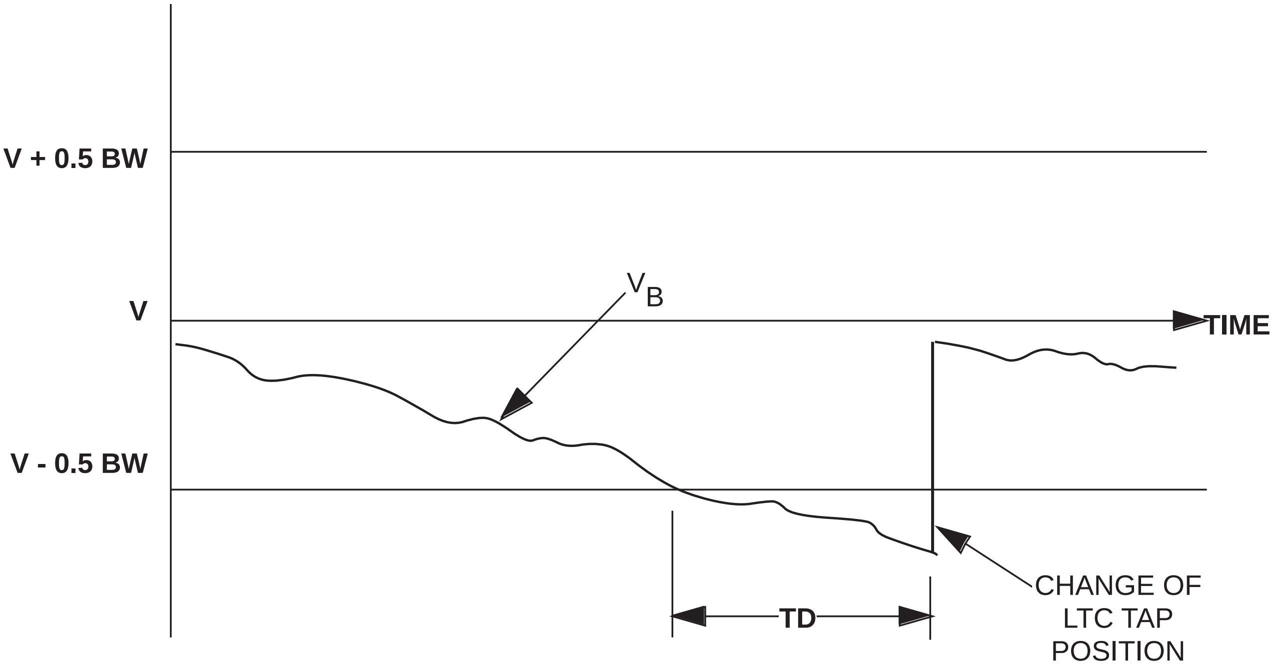
An intentional time delay is always included so as to avoid tapchanger operations when the voltage excursion outside of the bandwidth is of short duration. A good example case is that of a large motor starting on the system. The voltage level may be pulled low, but will be expected to recover in perhaps 15 seconds. To have made a raise tapchange for the short period would not significantly help in motor starting, and would require consecutive lowering operations after the motor came to speed, with attendant accelerated wear of the tapchanger. Consequently, the intentional delay is set, most often in the range of 30 to 60 seconds.

Figure 1 depicts the voltage on the substation bus, V_B, as a function of time without regard to line drop compensation. The tolerable voltage band is that within $V_{BANDCENTER} \pm 0.5\, V_{BANDWIDTH}$. In time, the bus voltage will drop below the bandedge, at which time the time delay is initiated. At the completion of the established time delay period, the control delivers a command to the tapchanger drive motor. Tap changer action causes a step change of the voltage, bringing the voltage level “in-band.„

Line Drop Compensation

There are usually two settings associated with line drop compensation which provide the means to individually program the control to compensate for one—the resistive, and two—the reactive voltage drop on the line between the transformer and the load location.

The difficulty in the use of LDC is that there is seldom a real-world situation applicable to the classical illustration of LDC application, i.e. a case where there is one distribution feeder of appreciable length, which is terminated in the only load for that feeder. In spite of this, LDC is often used with the recognition that the system may not be ideally suited for it.



V=Voltage Setpoint of tapchanger control

Figure 1 Illustration of the Interaction of Three Basic Control Settings

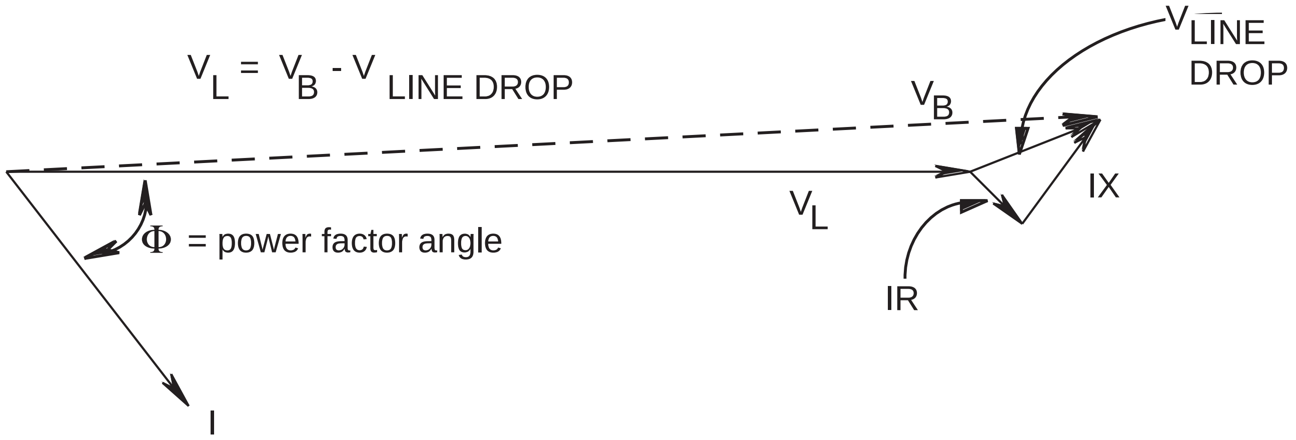


Figure 2 Phasor Relationships Applying to Voltage Regulation Using Line Drop Compensation

The underlying principle of LDC is that illustrated by the phasor diagram of Figure 2 with reference to the circuit of Figure 3. It will be recognized that the voltage at the load, V_L, will differ from the voltage at the bus, V_B, by the amount of the voltage drop on the line, $V_{LINE\ DROP}$. Figure 2 shows that there is a voltage phasor IR which is in phase with the load current, and a voltage phasor IX which is in quadrature with the load current which together sum to the $V_{LINE\ DROP}$. Once the line impedance is established, the $V_{LINE\ DROP}$ magnitude is a linear function of the load current. Also, the IR and IX phasors will rotate to maintain their angular relationship with the load current as the power factor of the load changes.

Many are confused by the fact that the LDC R and X settings are calibrated in volts rather than the ohmic value of the resistance and inductive reactance of the line. The value to be set on the control is the voltage drop on the line when the line is carrying CT-rated primary current.

An example simplified system diagram may be that of Figure 3 where the nominal 120 V signal from the VT is biased in the control by the LDC settings and the actual load current. It will be noted that, for the typical lagging power factor load, that V_B must continue to rise as the load grows in order to hold V_L at the setpoint (desired) voltage. If there is an unanticipated increase in the load, the control as defined to this point will simply command additional raise tap change commands, without regard for the bus voltage, V_B.

SUPPLEMENTAL FEATURES

Essentially all controls, electromechanical, analog and digital, accomodate the five basic functions. Digital controls clearly emerge from the pack when the control is required to perform supplemental functions. Some of the additional functions can be added as additional analog control packages, but are now commonly included in the one digital package.

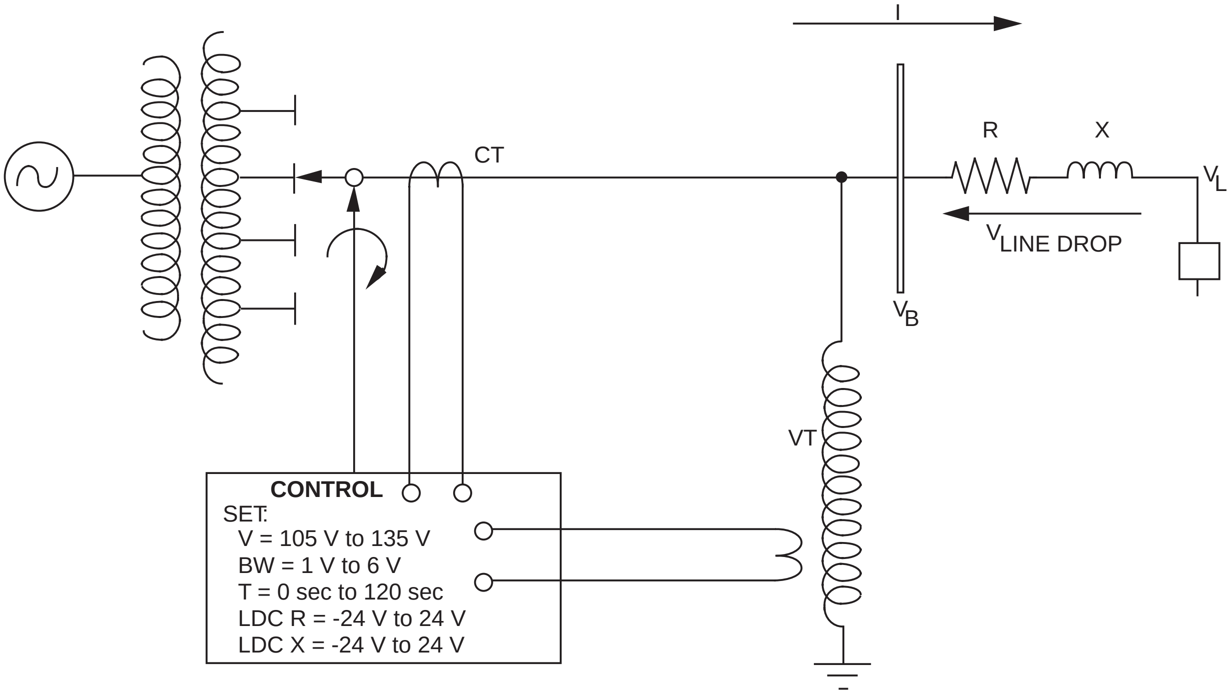


Figure 3 Control Circuit Employing the Five Basic Functions

Voltage Limit Control

That the voltage can rise too much due to LDC action forces consideration of system realities in that there is probably a first customer located very close to the bus which is seeing unduly high voltage by virtue of the inordinately high load. Yes—the paradox is true: high load can result in high voltage to the first customer when line drop compensation is used.

When this is a concern, the utility may wish to include a second voltage limiting control, or backup control. This is accomplished by simply routing the raise and lower outputs of the primary control through the backup control. The backup control responds only to V_B and as such may be set to restrict the tapchanger operation based on V_B without regard to the load, albeit at the expense of allowing the voltage at the load to fall below the desired level.

Voltage Reduction

System-wide voltage reduction may be imposed in order to reduce demand at critical periods. This is often implemented with analog controls by simply including a small voltage boost, as with a tapped autotransformer in the voltage sensing circuit. This boost in steps of typically 2.5, 5.0 and 7.5 percent “fools„ the control into commensurate steps of reduced output voltage. The need for this hardware implementation is easily avoided in the digital controls by a command, as from a dry contact closure, which results in the change of the voltage level setpoint. Also, digital controls are programmed to activate the reduction immediately upon receiving the command, without the need to first accomplish the panel time delay setting as is required by the analog equivalents. The actual percent reduction is programmed in software and is therefore much more amenable to system requirements than the limited selection of fixed values with the tapped autotransformer technique described above.

Reverse Power Flow

The reversal of the direction of the load flow in a distribution feeder step-voltage regulator application is characterized by (except for a brief transitional period) the continuing radial system operation, with the power flow in the reverse direction.

The control must therefore:

- recognize that the direction of power flow has changed
- employ the (previously) source side voltage to base subsequent tap change commands and
- reverse the tap changer motor drive commands (raise becomes lower and vice versa)

Analog controls require significant additional circuitry to detect the reversal and reverse the motor power logic. Digital controls already know voltage to current phasing relationships in order to accurately calculate line drop compensation and display the power factor; the mere recognition that this angle is between 90° and 270° is all the control needs to impose new rules for reverse power operation.

[The point regarding knowledge of the source side voltage will be treated later in this paper.]

If system conditions so warrant, the digital control uses alternate set points when the reverse power flow operation is active. Most notably, the same line drop compensation settings will not usually be correct for forward and reverse power flow operation.

Line Overcurrent Inhibit

A means is sometimes provided to inhibit tap changer operation based on line current magnitude in order to save tap changer contact wear at periods of severe overloading or low level faults. A supplemental analog device could be included for this purpose, or the digital control can be programmed to simply not permit subsequent tap changing above a programmed threshold of sensed line current.

Communication

Perhaps the most conspicuous difference between the digital and analog control products for the electric utility industry is the means by which communication is accomplished.

Communication associated with analog systems has been characterized by multiple transducers, one for each parameter of interest, and numerous analog signal inputs, usually 0 to 1 mA, at the Remote Terminal Unit (RTU). Using this procedure, reporting only bus voltage and line current on a per phase basis requires six transducers and six RTU inputs per feeder.

Similarly, outbound (commands) communications, while commonly referred to as “digital„, are truly only contact status changes used to initiate particular control actions, such as voltage reduction.

The new controls all accomodate some form of true digital (serial) communications, either one way or two ways. One way serial communication is such that, in response to a request, the control reports its knowledge of system conditions. There is no opportunity to change control setpoints or initiate control action such as a remote-manual mode of operation of the tapchanger.

Full two way communication allows for parameter readings, set point changes, configuration changes and control actions via remote means which would otherwise require an operator to be physically at the control. This is accomplished using a single communication line, traditionally RS-232, but more recently moving to other formats including fiber optics.

The use of serial rather than analog systems for communication not only greatly reduces the RTU hardware requirements for multiple input applications, but also makes feasible the communication of system parameters, in addition to voltage and current, e.g. power factor, kVA, kW and kVAr. With no need for additional hardware (transducers and RTU input cards) the serial communications can be formated to include the additional information without an additional hardware expense.

The matter of the communications protocol remains problematic. There is no accepted industry format to which all control manufacturers have subscribed, therefore, the central communications must adapt to each format in use. Recent efforts, notably by the IEEE Substations Committee, and EPRI may lead to uniformity in this regard.

Tap Position Knowledge

One emerging additional aspect of new controls is for the control to possess knowledge of the tap position on which the regulator or transformer being controlled is then operating. Traditionally, controls have only sensed the need to raise or lower the tap position and do so until a simple tap position limit switch prevents further excursion of the tap changer.

A control which knows the regulator tap position could be taught to accomplish additional tasks. The challenge is to obtain this knowledge without incurring significant additional expense.

Consider a system which, being initially established at a given tap position, could subsequently “keep track„ of changes in the tap position as commands are issued and feedback confirming the change is received. The control issues a Raise (or Lower) command. A short time later, the operation count signal would change state to reveal that a tap change has been accomplished. By presuming that the tap change occurred in the direction being commanded, the control calculates that the tap position is one-step higher (or lower) than when the sequence was initiated. If the system suffers no memory loss or other unanticipated disturbance, the knowledge of the tap position will remain reliably known. Of course, until confidence in such a scheme is well demonstrated, it should be used only for non-critical purposes.

Automatic Reverse Power Flow Operation Using Tap Position Knowledge Feature

One benefit of a “keep track„ feature in a feeder regulator application could be to permit calculation of the regulator source-side voltage using the load-side VT input, the tap position, the load current and an estimated regulator impedance. This procedure would replace the need for a source-side VT in order for the regulator to respond properly under reverse power flow conditions such as described by Figure 4.

In Figure 4, substation B is to be removed from service for maintenance. It is required to not interrupt service to any load normally fed from substation B, but rather to first parallel that feeder with substation A by closing the tie switch so that no loss of load occurs when breaker 52–B is opened. Note that when the switching is completed and all loads are fed from substation A, that the power flow direction in regulator B will have reversed. For regulator B to continue to operate properly in automatic mode, it must have been equipped with the means to sense its (normally) source-side voltage, as well as a control to perform per the description described under “Reverse Power Flow„„ above.

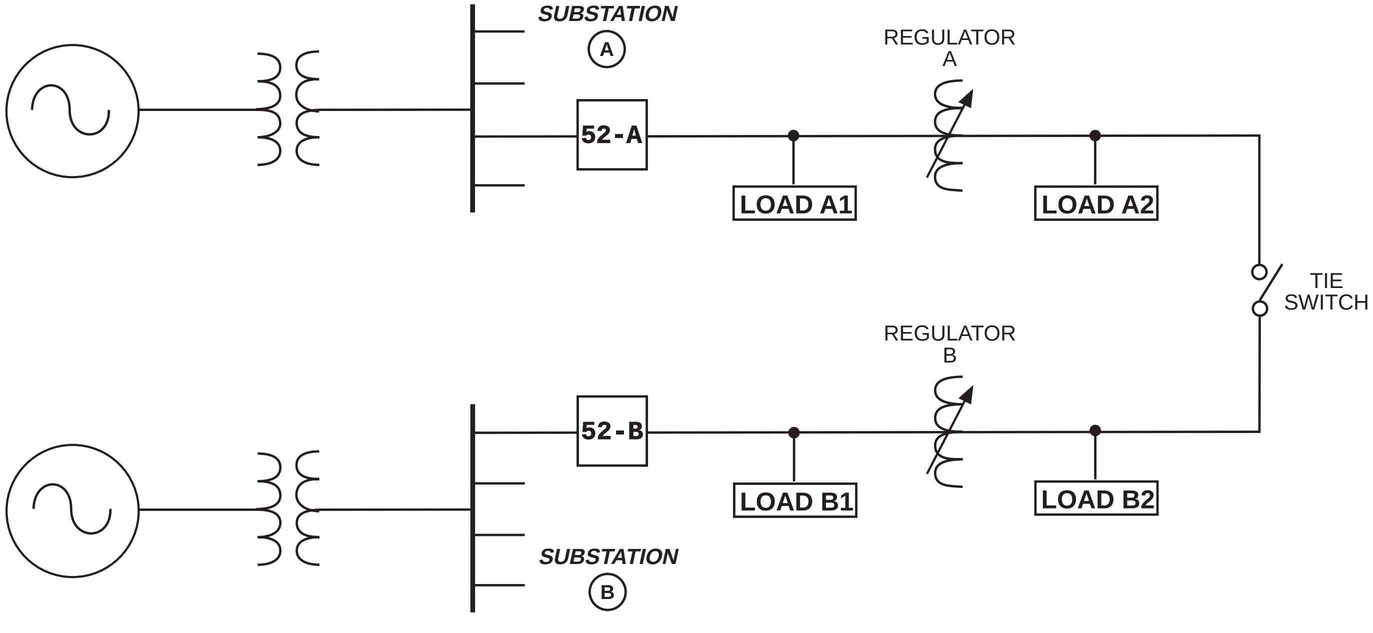


Figure 4 System Subject to Reverse Power Flow Operation

The switching sequence will commonly involve the need to send a lineman to regulator B to set the tap position manually to neutral (or some other predetermined position) and turn off the control as failure to turn off the standard forward-power-flow-only control would inevitably lead to that regulator running to the raise or lower tap limit once reverse power is obtained. Further, loads at position B1 would suffer from lack of regulation at the time most required, when they are on the end of a now doubly long radial feeder.

That few feeder regulators are today equipped for proper operation under the reverse power flow condition is attributed the capital expense involved, which must be justified by the avoidance of the need for manual intervention on the infrequent occasion when the power reversal is necessary.

Conversely, a new digital control which, after the appropriate line switching, is able to sense the reverse power flow condition, *calculate* the source-side voltage using parameters known to it with no supplemental VT, reverse the motor power drive and use special settings which come into play under the reverse power flow (such as a new, longer time delay to coordinate with regulator A) will have obvious advantage.

Thus, while it may not be possible to maintain the same level of voltage accuracy as for foward power flow conditions using one estimated regulator impedance, the voltage accuracy will apparently degrade by no more than about 0.75%, a very adequate solution for the few brief periods when this mode if operation is required. Of course, this represents a far finer degree of regulation if, as is commonly true, the alternative is to simply turn off the control.

DIGITAL CONTROL ALGORITHM DEVELOPMENT

There are two basic analytical procedures being used to derive the rms values of voltage and current required to be known by the control.

First, an algorithm may be written in discrete form which solves the defining equation for the rms value of a sampled signal:

$$Z_{rms_k} = \sqrt{\frac{1}{N}\sum_{r=0}^{N-1} Z_{k-r}^2} \tag{1}$$

The use of this equation will calculate the rms value of the waveform including any contribution from harmonics on the signal. The exact response of the system is a function of the waveform sample rate used and of the effect of any filtering applied which may attenuate the signal magnitude at harmonic frequencies.

When the rms quantities are determined in this manner, the system power factor will commonly be computed by measuring the phase angle between the zero crossings of the voltage and current signals, and relating this by a cosine function into the power factor. This method produces results which are analytically correct only when dealing with pure sinusoids and is susceptible to gross errors if the harmonic content is so great that zero crossings of the signal occur in addition to those defined by the fundamental frequency.

A second technique for the determination of rms values and the system power factor, which is immune to the deficiencies described above, is to estimate the parameters using a discrete Fourier transform (DFT).

Required from the algorithm are the rms values and phase angle of the fundamental frequency phasors. The DFT is executed in order to estimate these parameters while filtering the dc offset and harmonics.

To describe the DFT, assume the analog inputs are sinusoidal signals corrupted by noise. Using the notation

z_k = the sampled value of signal z(t) at k-th instant,

z_{k-r}= the sampled value of signal z(t) at r-th sample prior to the k-th instant,

and

N = the number of samples in one cycle of the fundamental frequency,

the computation of real (Z_{R_k}) and imaginary (Z_{I_k}) components of the complex phasor ($\overline{Z}$) are:

$$\begin{aligned} Z_{R_k} &= \frac{2}{N}\sum_{r=0}^{N-1} z_{k-r}\ \cos\frac{2\pi r}{N} \\ Z_{I_k} &= \frac{2}{N}\sum_{r=0}^{N-1} z_{k-r}\ \sin\frac{2\pi r}{N} \end{aligned} \tag{2}$$

where $z_{-1}, z_{-2}, \cdots z_{-(N-1)} = 0$ and N=16 samples per cycle. The magnitude $\left|\overline{Z}\right|$ and phase angle (Θ) of the phasor can be obtained as follows:

$$\left|\overline{Z}\right| = \sqrt{Z_R^2 + Z_I^2} \quad and \quad \Theta = tan^{-1}\left(\frac{Z_I}{Z_R}\right) \tag{3}$$

The rms value $Z_{1_{rms}}$ of the fundamental frequency component is given by:

$$Z_{1_{rms}} = \left|\overline{Z}\right|\ \sqrt{2} \tag{4}$$

The mathematical filtering characteristics of the DFT algorithm can be recognized by looking at its frequency response. The frequency response for the real and imaginary computation of the DFT algorithm is obtained for (N=16) using the Z transform technique and is given in Figure 5. It can be seen from this figure that the DFT rejects dc and up to the 14th harmonic of the fundamental.

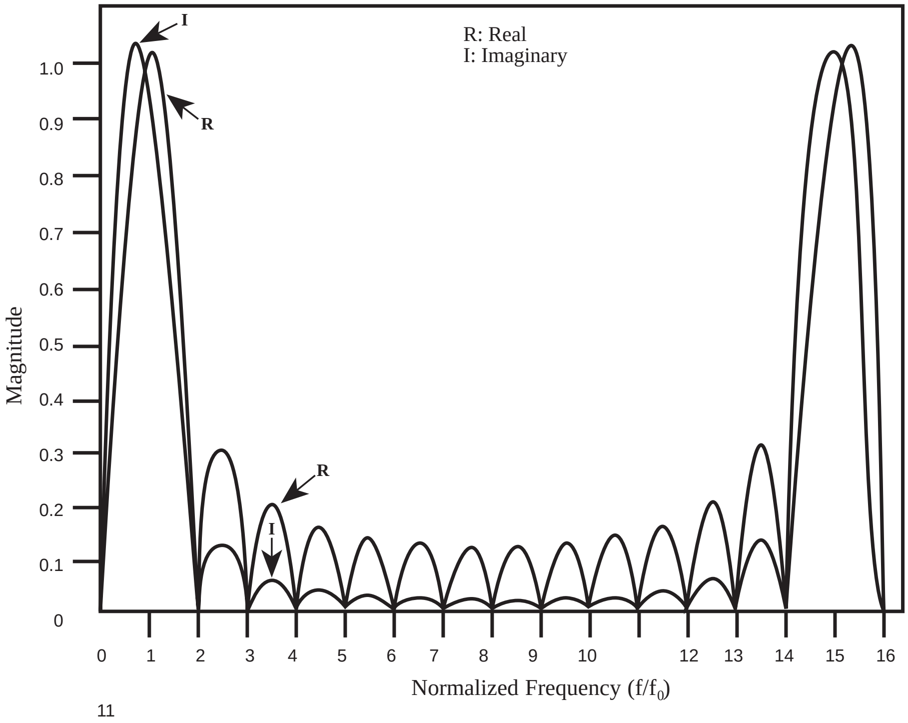


Figure 5 Frequency Response of the DFT Algorithm

Phasor rotation is a basic operation which is useful in many applications when the signals are represented in phasor form. This operation can be used to correct sampling delays in a multichannel data acquisition system when the sequential sampling technique is used with a single sample-and-hold circuit. This technique may be applied to bring the current phasor into time coincidence with that of the voltage in the two phasor sample application.

When two signals are sampled sequentially with a delay of ΔT seconds between the two channels, the phasor estimated at the second channel should be rotated by an angle $\Delta\Theta = \omega_0 \Delta T$ to correct the phase delay introduced by the sequential sampling. The rotated phasor can be obtained as follows:

$$\begin{bmatrix} z'_r \\ z'_i \end{bmatrix} = \begin{bmatrix} \cos\Delta\Theta & \sin\Delta\Theta \\ -\sin\Delta\Theta & \cos\Delta\Theta \end{bmatrix} \begin{bmatrix} z_r \\ z_i \end{bmatrix} \tag{5}$$

where $z_r + j\,z_i$ is the original phasor and $z'_r + j\,z'_i$ is the corrected phasor.

Computation of complex power can be easily achieved when the voltage and current signals are represented in phasor form. Let $\overline{V}$ and $\overline{I}$ represent complex phasors of voltage and current signals measured across a load. Then the complex power ($\overline{S}$) delivered to the load is given by:

$$\begin{aligned} \overline{S} &= \overline{V}\ \overline{I}^* = P + jQ \\ &= VI\cos\Theta + jVI\sin\Theta \end{aligned} \tag{6}$$

where real power is given by the real part of $\overline{V}\ \overline{I}^*$ and the reactive power is given by the imaginary part of $\overline{V}\ \overline{I}^*$.

The power factor is computed as:

$$pf = \frac{P_T}{\left|\ \overline{S}\ \right|} = \frac{P_T}{\sqrt{P_T^2 + Q_T^2}} \tag{7}$$

In this way, the power factor is calculated using the defining equation with no simplifying assumptions on zero cross phase angles.

CONCLUSIONS

The manner in which advances in electronics are enhancing traditional power applications is documented for the case of the transformer or regulator LTC control. This is especially true for the use of digital controls which, with communication and other advancements, makes possible the use of the control as the monitoring point of the system's nerve center. Further, it is recognized that being able to mathematically define the desired operation is tantamount to its implementation when considering digital control, with the result that many more features may be implemented with little additional hardware or expense.

Load Tap Changing Control

presented to

NATIONAL RURAL ELECTRIC
COOPERATIVE ASSOCIATION (NRECA)
March 24, 1996
Houston, Texas

by

J. H. Harlow
Consultant to Beckwith Electric Company
6190-118th Ave. North, Largo, FL 34643-3724, USA

Load Tap Changing Control

J. H. Harlow
Consultant to Beckwith Electric Company
6190-118th Ave. North, Largo, FL 34643-3724, USA

ABSTRACT

The control used for the tapchanger of an LTC transformer or step-voltage regulator is a prime illustration of electronic technology advances applied to the power industry. Electro-mechanical (balance-beam and induction disc), discrete static, integrated circuit static and now digital designs have evolved over the past forty years. This increased product sophistication has made possible many features beyond the primary objective of simple raise-lower commands in response to the measured secondary voltage.