Transformerless Power Distribution

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Abstract

Direct distribution of power from the generator to several customers without the use of step-up and step-down transformers is practical when consumers are located a short distance away and when sufficiently large current-capacity conductors are utilized. Problems, however, arise even with the use of conductors of sufficient current capacity (or ampacity) when consumers are situated away from the generator. Such problems have occurred at Mindanao State University, Marawi City. On campus, voltage drops in the transmission lines have been beyond tolerable limits. Computer simulation revealed that the large voltage drops in transmission lines were due to the inductance property of the transmission lines. The same simulation revealed that by adding automatic capacitors into the transmission lines during the times of heavy power demand and automatically disconnecting them during low power demand can result in customer-end voltages which fluctuate within reasonable limits. Actual implementation of automatically switching in and out capacitors has proven that indeed voltages at the customer end can be controlled and power losses reduced.

Transformerless power distribution coupled with the use of automatically-switched capacitors offers the promise of reduced power losses resulting in energy saving. This scheme offers tolerable voltage fluctuation at the customer end, thereby protecting sensitive electrical and electronic appliances from extreme voltage fluctuations. Electrical distribution companies engaged in the distribution of power as well as their customers are expected to benefit from this research.

Introduction

A typical electrical power system is composed of three main divisions, which are the following: generation, distribution and consumption. The most expensive among these is the distribution division. In the Philippines, the typical electric cooperative today invests around 54% to 122% of the generation and transmission cost[1], while in the USA, in the 1970s, electric utility companies, on the average, spent around

45% of the total system cost on the distribution component[2]. In addition, the electric utility company should not just provide electrical energy, but should also maintain the customer-end voltage at a level that is acceptable. In the Philippine setting, the nominal voltage level is 220 volts. It is at this voltage level that most electrical and electronic equipment are normally operated. Washing machines, for instance, are designed to work at 220 volts which may vary by +/- 10% from that nominal voltage level. This means that it could operate from 220 volts up to 240 volts. Ideally, the electric service company should provide a rock-steady 220 volts, but this is nearly impossible as there is no such thing as a perfect system. There will always be some voltage fluctuation. Voltage variations from the nominal level are all right provided these are within the tolerable limits of electrical and electronic apparatus. Thus, the distribution system is always designed to provide this nominal voltage with some allowable voltage variation.

History of the problem

For a good number of years, the MSU campus got its electric power from an NPV-operated hydroelectric plant through an electric cooperative. When MSU was unable to meet the demand to pay its electric bills on time, the distribution of power on campus was unilaterally cutoff, leaving the campus without electricity for several weeks. A committee was hastily formed in which this author served as a members. Due to the initial high cost of purchasing the generator and transmission equipment, coupled with the lack of funds, it was decided that direct transmission of power from a 300 kilowatt generator to the customer was the only option for the university. In other words, the distribution system would have to operate without the benefit of high voltage distribution-type step-up and step-down transformers. The use of distribution step-up and step-down transformers is a standard practice to minimize voltage variation at the consumer end.

Beginning of Diesel-Based MSU Power System

During the first week of operation, when consumers were obedient to the rules of using the limited supply of electricity, the voltage levels at their ends were within tolerable limits. But gradually, the demand for power increased. For those consumers located near the generator, voltages at their end were still within acceptable limits, but for those farther from the generator, their supply voltages were unacceptable. Sometimes, those houses located about 300 meters or more away from the generator experienced voltages as low as 150 volts! Even the use of automatic voltage regulators (AVR) would not provide a safe voltage level for sensitive equipment such as computers. On top of this problem was the inconvenience of frequent brownouts due to the frequent trippings of circuit breakers. This has resulted in the disruption of classes and loss of productivity. A solution was then sought which could alleviate the problem of huge drops in the transmission lines and reduce the incidence of unforeseen brownouts.

Analysis of the Problem

An initial calculation of voltage drops in the transmission lines turned out to be inconsistent with the actual voltage drops. There was nothing wrong with the size of transmission conductors since the measured actual line currents were less than the conductor ampacity. The data on the transmission line resistance were presumably correct as they were obtained from the manufacturer. Even the inclusion of a phenomenon such as "skin effect" which tended to increase the resistance of the line conductors could not justify the actual voltage drops. Eventually, the problem was traced in the assumption that since the transmission lines were less than 2 kilometers, the effect of line inductance on the consumer-end voltages was negligible. This assumption, later, was proven incorrect as seen in the following analysis:

To a first order approximation, the source voltage (Vs) and receiving end or consumer end voltage (Vr) are related by the equation:

$$Vs = Vr + IL * sqrt(3) * [R_{Line}*\cos \theta + X_{Line}*\sin \theta] \qquad (1)$$

where: R_{Line} = the transmission line resistance

X_{Line} = the transmission line inductive reactance, and

$\cos \theta$ = Power factor (Pf) of the load

Equation (1) can be rearranged to get:

$$Vr = Vs - IL * sqrt(3) * [R_{Line}*\cos \theta + X_{Line}*\sin \theta] \qquad (2)$$

Actual measurements of voltages and line currents gave the following:

Vs = 250Volts   IL = 230Amperes

R_{Line} = .069 Ohms $\cos \theta$ = 0.70

Assuming the line inductance was negligible, the predicted receiving end voltage was

Vr = 250Volts – 230*sqrt(3)* .069* 0.70 = 250 – 19.24 = 230.7V

However, the actual measured receiving end voltage was about 185 to 195 volts. Definitely, there was something that was missing, and that was the inductance of the transmission line. For the transmission setup serving the 4th to 8th street area, the calculated reactance due to the line inductance, according to a published table,[3] was 0.138 ohms. The line reactance X_{Line} was obtained directly from the Line inductance L_Line by the equation:

$$X_{Line} = 2*3.14158*60Hz* L\_Line$$

The receiving end voltage was recalculated on the assumption that the line inductance was not negligible:

Vr = 250Volts – 230*sqrt(3)*[.069*0.70 + .138*.71] = 250 – 58 = 191 V

which was close to the actual measured voltage.

Solution

The foregoing analysis showed that the reactive part of the transmission lines was, after all, not negligible and, in fact, accounted for more than half the line voltage drop. One practical solution that was found was reducing the effect of the inductive reactance of the transmission line by way of adding capacitors, since capacitors generate or provide reactive power.

Experiments were conducted on 20 and 40 watt fluorescents using various values of capacitors and it was found that, indeed, the total current required by fluorescents with added capacitor have decreased by a considerable 35% to 40%. Experiments on refrigerators with and without capacitors were also performed and the result verified that capacitors can in fact reduce the net current.

Computer simulations using softwares known as **PSPICE** and **MATLAB** were then used to design the correct value of capacitors to be added to the transmission system. The simulations revealed that indeed capacitors worked to decrease the transmission line currents, thus decreasing the line voltage drops which in turn improved the receiving-end voltage. The following are some of the simulation results:

Parameter	Without Capacitors	With Capacitors
Line Current IL	200 Amperes	160 Amperes
Receiving-end Voltage	198 Volts	220 Volts
Power Losses	8.2 Kilowatts	5.4 Kilowatts

Table I. Simulation results for 4th to 8th street transmission

line with and without capacitors

Parameter	Without Capacitors	With Capacitors
Peak Load Current	45 Amperes	23 Amperes
Power Losses	------------	* Should be less

Table II. Simulated current reduction for PLH North Wing

Girls Dormitory with and without capacitors assuming

receiving end voltage to be constant.

As can be seen in Table I, the added benefit was the corresponding reduction in power losses which amounted to a saving of 2.8 Kilowatts for transmission lines serving the 4th to 8th street houses.

Development of Prototype ACR

The experiments and initial computer simulation were in agreement as to the effect of adding capacitors into the transmission line system. Additional computer simulations were done on a realistic transmission line system in which the load current varied, thus, the line current also varied. In this case in order to limit the voltage fluctuations at the receiving end voltage, several values of capacitors had to be used. During times of heavy load current demand, a large valued capacitor was added into the system but when the demand was light, a correspondingly small sized capacitor was used. It is from this concept that a prototype automatic current reducer or ACR was developed. The ACR operated by automatically switching in additional groups or banks of capacitors in times of heavy line current and switching them out during lighter load current. The automatic switching in and out of capacitors based its action on a current sensor coupled to an opamp which in turn drove a mechanical and solid state relay. Two prototype ACRs were designed and fabricated. One of the ACR was installed at the entrance of the administration building of MSU campus where the receiving end voltage was relatively constant. The other ACR was installed near the end of the long transmission line serving the 4th to 8th street houses where receiving end voltages were found to fluctuate by a wide margin. On the ACR operating at relatively constant voltage and installed at the administration building, the following results were obtained:

Line Current IL Without Capacitors	Line Current IL Capacitors	Capacitor Value	Current Saving
49.3 Amperes	32.1 Amperes	360 uF	17.2 Amperes
46.7 Amperes	29.0 Amperes	360 uF	17.7 Amperes
45.0 Amperes	25.0 Amperes	560 uF	20.0 Amperes
43.0 Amperes	28.0 Amperes	685 uF	15.0 Amperes
52.5 Amperes	36.5 Amperes	685 uF	16.0 Amperes

Table III. Current reduction using ACR installed at the administration building.

On the ACR installed in the 4th to 8th street area, the only information that was gathered was the report by a neighbor that the voltage at their outlets had increased. This could only mean that the line current have decreased and so have the power losses in the transmission lines.

Conclusion

In situations where Electric Utilities do not have the benefit of step-up and step-down transformers, the use of capacitors can help reduce the receiving-end voltage fluctuations to an acceptable level. Banks of capacitors must be automatically switched in and out of the transmission system in order for this scheme to be practical. This idea has led to the development of a prototype apparatus which this author calls the Automatic Current Reducer (ACR). One of the implications of the results obtained in Table III, is

that the ACR not only reduces the effective load current but it also tends to increase the capacities of transformers, switching equipment, transmission lines and generator. As a result, electric cooperatives (there are many of them in this country) do not have to purchase distribution transformers as often as when ACRs are not utilized. This further implies saving our environment as wastes and pollutions are always generated whenever a transformer is produced. The added benefit of reduced system power loss with the use of ACRs in increased earnings for electric utility companies.

Notes

[1] "Electric Coops distribution costs high", *Manila Bulletin* (Feb. 2, 1998, p. B-5).
[2] Anthony J. Pansini, *Basic Electrical Power Distribution*, Vol. 1, 2nd Ed. (Hayden Books).
[3] W.C. Bloomquest, "Power Factor Improvement." In *Industrial Power Systems handbook*, ed. Donald Beeman. New York: McGraw Hill Co.