A Brief Review of Electric Power Energy Management Systems

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1. Economic Aspects of Energy Management

1.1. Introduction

The Energy Management System or EMS as we know it today had its origin in the need for electric utility companies to operate their generators as economically as possible. That there was ample cost justification for this has been demonstrated many times. At this point, I shall refer to an electric power system as consisting of generators, transmission system, and the distribution system to customer loads.

To operate the system as economically as possible required that the characteristics of all generating units be available in one location so that the most efficient units could be dispatched properly along with the less efficient. In addition, there was a requirement that the on/off scheduling of generating units be done in an efficient manner as well.

Finally, the scheduling of generators with limited fuel or water supplies were incorporated in energy management systems. This allows operators to further reduce the cost of operation by taking advantage of cheaper fuels or hydro power.

When operating within a vertically integrated electric utility - i.e., one which owns and operates the generation, transmission, and the distribution the economic dispatch and scheduling of generation is usually done to minimize the total operating cost of generation. When the electric system is unbundled, the economic dispatch and scheduling is done on the basis of prices bid to a central office.

1.2. The costs of Generating Electric Power

For a thermal plant, the cost of generating electricity is chiefly the fuel burned. To the fuel costs are sometimes added the associated costs of maintenance and repair. The fuel is proportional to how much power is being generated, while the other costs may be proportional to both the power being generated as well as the amount of control action being asked of the generator.

There are also capital and operating costs that have little to do with the hourly production of the generating unit. These costs are not usually taken into account in the operation of the generator, but they play an important part in the manner in which the power production facilities are managed. Ultimately, the utility must decide whether the production plant personnel where the plant is located are responsible for its efficiency or whether the operating personnel at the EMS are responsible. In either case, there are important compromises that must be made. When the production efficiency is the responsibility of the power plant personnel, they will try to make the plant operate at its most efficient point - with no regard for control actions that are trying to regulate frequency. They are also responsible for the maintenance and will strive for few plant outages. The operating personnel on the other hand may treat the plant differently, paying attention to control as well as operating economics.

1.3. Economic Dispatch: Scheduling Generation to Minimize Cost

The process of scheduling generation to minimize operating cost has historically been called Economic Dispatch. In this calculation, the generation costs are represented in the computer system as curves, usually piecewise linear, and the overall calculation minimizes the operating cost by finding a point where the total output of the generators equals the total power that must be delivered and where the incremental cost of power generation is equal for all generators (if a generator is at its upper or lower limit, that generator's incremental cost is different).

This calculation is made continuously on some computer systems, but more practically it can be made every few minutes. It is the responsibility of the automatic generation control program to allocate the generation to each plant in accord with the economic dispatch program output, as well as keeping the system tie lines and frequency at the desired point.

Traditional economic dispatch calculations take account of the network losses through the use of incremental loss factors. The state of the art method of accomplishing this is to run what is called an Optimal Power Flow (OPF) which minimizes the generation cost while taking account of the entire transmission system and all its constraints.

1.4. Automatic Generation Control (AGC)

The basic control of generation on a power system is done through the control of the electrical frequency measured at one of the high voltage buses in the system. If the frequency drops below nominal there is a need for increase in generation and if the frequency rises above nominal there is a need for less generation. The control of generation is done as a supplementary control to the basic governor controls on the generators themselves that work to maintain system frequency by raising or lowering the energy into the primemover of the generator. The supplementary control, known as automatic generation control or AGC accomplishes more than just frequency control however. If the power system is being maintained in economic dispatch, the AGC is responsible for allocating generation changes in a manner that the new total generation matches the needed power for the system while being allocated in an economic manner. In addition, if the electric system is interconnected with other neighboring systems, the AGC must not only maintain frequency, but it also maintains the net power interchange schedule according to specified contracts that are in place.

In the future, generating companies may offer frequency control and load following as extra "ancillary services" to be paid for separately by the transmission system company.

1.5. Unit Commitment: Scheduling Generating Units ON and OFF

The fact that the load on a power system goes up and down as people and business raise and lower their load requires that electric utility operators schedule units to come on during high load periods and go off during low load periods. Usually, the operators require enough generating capacity to meet the maximum expected load and then add an additional amount of reserve to be used in the event of the outage of one or more units.

The on/off cycle of generating units has been a particularly difficult scheduling problem to solve. By its nature, it requires the solution of variables that are either 1 or 0 and is therefore a hard problem. The problem was solved reasonably well using dynamic programming for many years and recently has been solved with much more precision using a technique known as Lagrange Multipliers.

1.6. Fuel/Hydro Scheduling: Scheduling Generation with Limited Energy

Many times, the power to be generated comes from a fuel source that is limited. These limits can be in place because of the plants gas, oil or coal supplies. In the US the gas suppliers write what are called “take or pay” contracts in which the utility agrees to pay a fixed amount for a specified number of cubic feet of gas. The utility then has the responsibility to burn that gas in an allotted time - and if it doesn’t use the gas it simply losses it. Therefore there is a great incentive to burn the gas within the allotted time schedule.

A very similar problem exists in the scheduling of hydro plants where water must be passed through hydro turbines to meet a given schedule. The complicating factor with hydro plants is the constraints that are placed on the plant by the river system and by other hydro plants that might be in series on a river.

Finally, there is the problem of scheduling pumped storage plants where the economy is derived from the fact that the plant draws electric energy from the network when it is inexpensive and stores that energy as water that has been pumped to a higher elevation. The energy then can be returned to the system by generating with the same water. Usually the generation is done during periods when the cost of power is high. In this way a pump-generate cycle can actually reduce the overall cost of operating the power system.

1.7. Interchange of Electric Energy

Power has been bought and sold for decades around the world as wholesale transaction among electric utilities. In the USA there are different kinds of interchange depending on the purpose for the exchange of power. Some interchanges are for the purpose of obtaining economies when a low priced seller sells to a higher price system. These are called “economy interchanges” and may be on the way out in many parts of the US. The other types of interchange are long range (beyond one hour) and are there for the purpose of supply large blocks of power at favorable prices.

1.8. Open Access Transmission

Open transmission systems operate on the idea that all of the power plants should be managed separately, and in fact they may be owned by companies that do not own any transmission or distribution equipment. The idea is to have a transmission system provide transmission services to the generators which in turn directly sell their power to distribution companies or large loads. In such a system, the EMS does not have to have the cost data normally associated with economic dispatch. Rather, it receives bids from the generators to supply power to the loads and it selects the lost bidders as those who will supply energy.

This concept has been fully implemented in Norway and Great Britain, it is being discussed in Europe and will be implemented next year in the USA.

1.9. Future Developments in the Economic Operation of Power Systems

Several new developments are taking place in the future that will affect the economics of power system operation. The first has to do with the fact that air pollution must be reduced in countries where large numbers of fossil fuel plants are running. In this regard, the US Congress has passed new laws which are referred to as the "Clean Air Act".

The clean air act laws have mandated that utilities reduce NOx and SO2 emissions. Further, since the emission of SO2 is a total amount for the entire country, utilities are allowed to trade "emissions allowances" with each other. An emission allowance allows a utility to emit 1 ton of SO2. A utility may choose to shut down one of its generators and sell its allowances to another company. The effects of this law will be felt in the daily dispatch, unit commitment, the operation of fuel constrained and hydro plants as well as the way utilities price transactions to each other.

Other aspects of economic operations and scheduling that will become very important are the inclusion of system security directly into the way the system is economically dispatch and scheduled. The difficulty here is to place a cost on the actions taken to gain secure operation so that they become cost justifiable with the actions taken for purely economic reasons. Thus we shall see scheduling programs such as unit commitment and fuel or hydro scheduling programs that are constrained by static and dynamic security limits, the limits being justified by the increased "cost" of operation when risks of system failure are taken into account.

2. Power System Security

2.1. Introduction

System security is that aspect of system operation that allows the operators to determine whether an unforeseen event such as a line or generator outage or a fault will cause equipment to be outaged thereby causing other equipment to overload and cause more outages, etc. The resulting situation can result in a low frequency, low voltages, severe overloads on transmission lines and transformers, or an instability. Any of these can remove a large number of pieces of equipment and leave a large number of electric customers without power. The costs in lost revenue, customer losses and equipment damage can be extremely large.

In the United States, we usually trace the emphasis on system security in EMS to the large scale blackouts that happened in the mid 1960's when very large areas of the US and Canada were left without electric power. Engineers realized that the security of the power system had to be managed properly so as to avoid serious problems.

In addition to the need for monitoring system security, there appeared a major shift in the late 1960's and early 1970's in the basic design of an EMS. Originally the generation control and scheduling system was thought of as one system. The supervisory control system used to monitor and control circuit breakers and other equipment in the transmission substations was considered a second separate system. Realizing that both the supervisory system and the generation control system used communication links and computers meant that there would be an advantage to combining them.

The result is the modern EMS which combines Supervisory Control and Data Acquisition (SCADA) capabilities along with generation dispatch, scheduling and control capabilities. Modern EMS's now had the ingredients necessary to provide operators with advanced security analysis capabilities. This feature is considered absolutely necessary in operating a power system as it allows operations personnel to make the most efficient use of the transmission system by loading it up to its limit without placing it in an insecure state.

2.2. Monitoring: Alarm Processing and State Estimation

Secure operation requires that operators monitor the system for existing conditions that might be cause for action (such as voltage or power flow limit violations, abnormal switching as a result of a fault, etc.) as well as make predictions of system conditions that might occur if an event such as a fault or a line or generator happens.

Monitoring the power system takes place in two ways. The basic process of taking measurements in the substations, transmitting the values to the central computer and comparing those values to stored limits is known as alarm processing. In addition to the processing of "analog" type alarms, the EMS also monitors the status of various binary devices (breaker and switch open/closed status, temperature under limit/over limit indicator, etc.) together these indicators make up tens of thousands of "points" that must be monitored and displayed to the operators.

The main emphasis the design of alarm processors in recent years has been to bring these points to the operators attention very rapidly and this has meant that operators can be overloaded with hundreds of new alarms to read in a few seconds. To help in this case, knowledge based alarm processors have been developed that can filter out all but the most important alarms and then present summary alarms so the operator can deduce the situation quickly.

When it comes to the transmission system, however, there is a need to further process the real time measurements so that a complete mathematical model of the system can be built. This is done using a power flow model and a state estimation algorithm which can read many redundant measurements and calculate the statistically most probable set of states (voltage phase angles and magnitudes) existing on the network. In addition to providing the states, the state estimator has the ability, given the right set of measurements, to detect and identify measurement that are bad. The bad measurements are removed and reported to the operators so they can be recalibrated.

The result is a much greater trust in the readings of the measurements themselves. Present computer technology allows one to design a state estimator that runs at the speed that data is gathered and thus would always present state estimated data to the operators.

Problems in the state estimation systems in present use usually center on the equivalent network used to model the neighboring systems. Since there are few instances where utility computer systems have access to information about the neighboring systems, the results depend upon using poorly formulated forecasts of what is happening to the neighbor’s system - and this can lead to nonconvergence of the estimator algorithm or to unusable results.

2.3. Static Security Assessment

Once a state estimate is complete the operators have a model of the power system as it presently exists. The next effort is to test that model for a large number of outages to determine if the system can recover from the outage without problems. The outage events or contingencies can be modeled using a power flow program by running the contingencies one at a time. However, even with the most powerful computers this is a difficult process since the single contingencies plus multiple contingencies may number in the thousands and the total time for all of the power flows on all the contingency cases would take hours.

Since the operators need to know which contingency cases are going to give trouble, there must be a way to select the troublesome cases from among all the cases which report no trouble. Such “contingency selection” or “contingency screening” algorithms have been developed and work quite well. They work by a combination of fast approximate power flows and other analytical techniques that make a prediction of how much limit violation a contingency will produce without solving the entire power flow.

Once a limit violation is predicted and verified by running a power flow on that case the operator must take action to relieve the violation. This may take the form of generation shift, switching the transmission system, or in extreme cases load shedding. Of course if the overload is one that may be tolerated for a significant period of time, the operators may do nothing and “ride it out”. Often, the operator must run a calculation to determine the best means of avoiding a contingency and this involves placing the contingency as a constraint in an OPF.

2.4. Security Constrained Optimal Power Flow

Knowing that an OPF can accommodate a constraint that will guarantee that a contingency overload is eliminated has led to an elaborate program that includes the contingency analysis and an OPF wherein all contingencies are tested, and all overloads are converted to constraints and placed into the OPF. After solution it must be iterated through the contingency analysis again to be sure it has found all bad cases. The end result is a dispatch which guarantees that all contingencies tested are not going to result in trouble.

2.5. Dynamic Security Assessment

One of the grand challenges in the past five years has been to develop a means to asses whether the current power system can withstand a severe fault condition that would result in a system instability. The problem here is similar to the static security analysis in that there are thousands of fault cases that need to be tried, and the time to solve all of them is prohibitive. In fact, research groups working on this problem have targeted a selection procedure that would eliminate all but fifty cases that would then have to be solved. However, even fifty cases that must be solved in great detail presents a very challenging problem - since each case may take many minutes to solve.

Most researchers in this area are suggesting that advanced computer architectures such as vector processors or multiple processor machines must be used.

2.6. Future Developments in Security Assessment

One future development in the area of power system security that must be addressed, as mentioned before, is the need to provide a cost vs. risk measure for correcting for a contingency (be it a static problem or a dynamic problem). One can readjust the system to protect against contingencies and run its operating cost up so much that it is too expensive given the level of risk avoidance needed.

2.7. Security Analysis and Open Transmission Access

When the transmission system is to be operated as an open system there is a different problem in maintaining system security. First, there is the need to allow independent generating facilities to obtain access to the transmission system in a safe manner. That is, they must contact the transmission system operator and “reserve” transmission capacity for their transaction. The reservation process will necessitate the testing of the system for system security while modeling the proposed transaction.

3. The Operator Interface and Intelligent Applications

3.1. Introduction

In the mid 1980’s two new aspects of EMS design began to emerge. The use of full graphic displays and the incorporation of intelligent applications to aid the operators. The full graphic displays replaced so called “character graphic” displays that required alphanumeric characters as well as graphic symbols to occupy fixed locations and fixed size and format on the screen.

The newer full graphic screens allowed the software to address each pixel on the screen and to set its color and brightness. Alphanumeric characters could be located anywhere and in any font and size. Graphic displays were possible that could also be scaled and moved anywhere. Single substation one line diagrams became a “world map” where the entire power system one line diagram was represented on a single graphic that the user “paned” over and “zoomed” in on with increasing level of detail were designed. Finally, taking the clue from modern graphical user interface design for personal computers and workstations, the power system displays were provided with multiple window capabilities that could be opened and overlapped as an operator might deem useful for any particular circumstance.

The use of intelligent systems paralleled the developments in artificial intelligence research around the world. The first applications involved the ability of a computer code to incorporate knowledge about the operation of a particular aspect of the power system, and then to manipulate that knowledge along with real time status and measurement data to draw conclusions about the state of the system. Later came the use of artificial neural networks that could be set up to allow the computer system to observe patterns of behavior on the system and “learn” or adjust their response accordingly.

3.2. Graphic Displays

Full graphic displays brought a new technology to the EMS area. This was a revolutionary change in the way information was displayed, much as the introduction of CRT displays was revolutionary over the static wall maps and strip chart recorders.

The full graphic displays allowed operators to see the power system in new ways. The one line diagram can be made up as one diagram that the operator moves around on (pan) and then magnifies for detail (zoom). As a data entry tool, the full graphic displays allow the operators to place the cursor on a diagram and hit a function key to bring up a window with detailed data entry for that component.

By using windows to view different diagrams or tables of numbers, the operators can combine the needed information from various parts of the EMS to solve problems.

Where the graphic displays should have the greatest impact, and to date have not, is in the area of three dimensional graphics, unusual graphics that allow comparison of values in new ways, and unusual uses of color such as is done in scientific visualization. Many of these graphic display techniques do not tax the ability of the graphic display software, but rather, they tax the imagination of the engineers making up the displays and the operators to properly use them.

3.3. Knowledge Based Expert Systems

Knowledge based systems involve the use of expert system software which allows the encoding of knowledge about a power system into the computer and its manipulation for solving special problems. The knowledge is encoded in the form of production rules which allow the expert system inference engine to “reason”. As such, an expert system allows one to set up the solution of a problem that would be impossible to formulate as a mathematical algorithm (as are most of the applications in an EMS).

Often, the operations personnel want information displayed in a certain way, or they want it processed in a manner that reflects the system operating conditions. For many years, operators found that alarm displays had been designed to meet high performance but neglected to pay attention to the operator’s abilities to comprehend information - the result was too many alarms on the screen for an emergency event. The problem was not successfully attacked until the technology of expert systems became available wherein the knowledge of how to treat various alarm conditions was encoded into a knowledge base and each alarm was processed accordingly. The so called Intelligent Alarm Processor (IAP) gives operators a summary display of only the key alarm messages during an emergency so that they have time to read and understand what is happening.

Expert systems are also very powerful at solving diagnostic reasoning problems. Therefore many EMS systems include expert systems to diagnose faults on the power system using breaker status, switch status, and relay target information. This process is made even more powerful when a model of the power system is built from the SCADA system data base. The expert system is loaded with knowledge about the power system, about how the relays operate, and about what to expect from faults, stuck breakers, and improper relay operations. This knowledge, together with the current system model and the real time indications of breaker/switch status and relay targets, is used by the expert system to tell operators the most likely location of faults as well as alternate locations that should be investigated.

Beyond this, expert systems have been employed to allow engineers to design various “smart” applications that aid the operator in coping with the difficulties of running advanced complex applications. Often, the operators will not use the advanced application software if it is too difficult to set up the data before running it or too difficult to interpret results. In these cases, the engineers in the operations group can use an expert system to aid in data set up and results interpretation.

3.4. Neural Network Applications

Neural networks are an artificial intelligence tool that attempts to program a computer to act as though it contained neurons similar to those found in the human nervous system. The human nervous system is able to recognize patterns that are input to the nervous system after it has sensed them previously and been taught the meaning of the pattern. This is how we learn and store knowledge.

In an artificial neural network application, the neurons are simulated by software together with a means of presenting the network with patterns to be learned and a means of instructing the network as to the meaning of the pattern. The neural network can theoretically be taught anything - however, computers cannot store and process nearly as many neural network nodes as the human nervous system and brain, so they are far less intelligent. None the less, the neural network research has begun to show great promise in those aspects of power system operation where patterns must be recognized.

One such area that has received a great deal of attention is the application of neural networks to the prediction of electrical load. The idea being to present the neural network with many historical patterns containing the load behavior, some weather data, the time of day and season, etc. and have it “recognize” these patterns so that when presented with weather predictions and time, it can predict the load for some period ahead. The problem with this technique, in my opinion, is that the builders of such systems have not gone far enough to include all the available weather data such as digitized satellite photos of weather patterns over the past few days as well as numerous other weather data measurements of temperature and pressure that are available by data link from private weather monitoring companies.

Another application of neural networks that has been tried many times is the prediction of static or dynamic security. The idea is to run a large number of contingency analysis studies and present the results to a neural network together with a list of overloads and voltage violations for each case. In tests done so far, neural networks can be programmed to successfully recognize those conditions on the power system that lead to trouble, and since the execution of the neural network is so fast it is an ideal application within the EMS. However, there is one aspect of this development that simply has not been solved adequately - the “training set”, that is the set of all cases used to train the neural network, must include a very large number of combinations of load, unit commitment, network switching topology and interchange contracts. When an adequate number of cases is contemplated, it is usually seen that the number of cases is much too large to ever successfully generate and then train the neural network. Only in those cases where all the combinations need not be tried can the neural network become a viable technique for security assessment.

Future Developments in Operator Interfaces and Knowledge Based Systems

The future should see more and more uses for full graphic displays. This is particularly true as engineers are able to formulate three dimensional displays and other visualization techniques to show complex situations to operators. At present, there is no systematic body of knowledge that leads one to create such displays. They are all one of a kind developments and progress is very slow.

The knowledge based expert system and neural network applications are growing every year and give every indication of being a standard technology used in EMS. The programming environment available to developers of expert systems and neural networks is much more complete today and the ability to interface them to the existing real time data and static data of the EMS itself is much easier. I expect to see knowledge based applications advance to the point where fully automatic operation of substations is a reality (this would include protection system operation, fault diagnosis and restoration systems that took account of all switching rules). Very complex applications that are guided by knowledge base systems should become available in the next few years as well.

Neural network applications to load forecasting that take account of the wealth of weather data available will eventually become available. Neural networks will also be in place to recognize control problems with generators such as whether a unit is responding to control properly and how much regulation can be expected from the unit.

Ultimately, we can summarize the application of knowledge based systems by planning for completely automated operation of various parts of the power system. This is necessary since human reaction time and ability to comprehend the vast amounts of data are simply too limited to operate the system as close to its limits as desired.

4. Hardware and Operating Systems

4.1. Introduction

The computer industry throughout the world is going through vast changes at the present time. These changes are in the direction of systems that no longer use proprietary operating systems, proprietary data bases, proprietary communications protocols, etc. Instead, the users of computers are demanding standardization of the operating system, the data base and communications.

As a result, users are not purchasing large mainframes in the numbers they used to, but are purchasing personnel computers, workstations and data base servers that are connected via networks. These systems use standard (although to be accurate, no real industry wide standard is in use yet) operating systems and communications protocols.

4.2. Open Systems and computer communications

The advent of modern networking of computers together with very power personal computers, workstations and data base servers is having a profound effect on all aspects of computer usage in electric utilities, including the design of a modern EMS. Traditional EMS systems were designed around large supermini or mainframe computers, usually in pairs for reliability. If the users of an EMS desired to add a new application to the EMS it had to be programmed in the existing computers and made to interface with the data base as designed for that computer system.

This inflexibility in adding new applications and the inability of being able to change, upgrade or alter applications led to systems for many years where these applications were run in “add-on” computers that were tied to the main system through data links. Today, this scheme has been taken to the extent where such systems are built entirely of data linked personal computers, workstations and data base servers. If an application needs to be added or upgraded, a new workstation is added to the network to run it (or an older workstation is changed out for a newer one with better performance.)

Other aspects of this revolution include an almost standardize use of UNIX as the operation system (almost, since UNIX itself is not a standard operating system across different vendors of computer products.) Finally, the use of “standard” data base tools and access codes allows applications written by different organizations to use the data in the EMS and to display that data on the Graphical Display System.

The net result is not just a revolution in the operations department, but a joining of all computing and data base services throughout the entire utility company into one (hopefully) united and coordinated system with free exchange of data throughout all levels of the business organization.

4.3. Data Bases in EMS and the need for a Programming Environment

Traditional EMS architecture included a data base where all the information about the generation and transmission system was stored. Included also where the background information for displays and all the SCADA system point identifier information.

Users of such systems had a big problem however. The amount of data was enormous and the power system itself was always changing so that the data had to be updated or maintained constantly. Thus there was a need for modern data base management tools that allowed the data base maintenance staff to make queries, to use data entry template displays and to track changes. However, the data base management software, while powerful in its abilities to enter and track changes, was not efficient in allowing programs to get large blocks of data quickly for applications, nor was it good at allowing SCADA or display applications to get at smaller chunks of data quickly for updating real time data tables and for bringing up displays quickly.

The result was the development of a two tiered system of data storage. The base of this system is a modern relational or object oriented data base with all the query language capability, template displays for data entry, and auditing information to track changes. This data base is the one used by the data maintenance staff to update the system as construction adds to substation configurations, or generator data changes. The second tier is a data base that is designed for high input-output performance. This data base is often called a “flat file” data base because it relies on adjacent storage of commonly grouped data to speed its transfer into applications.

To use the two tiered system requires that the high performance flat file data base be updated or “populated” to use the current jargon. Thus when changes are made to the first tier they must then be transferred to the second tier for use by the EMS applications.

5. Operator Training Simulator (OTS)

The operators of a power system need to be trained to react to emergency situations quickly. Much like airline pilots or nuclear plant operators, power system network operators are trained using training simulators that mimic the conditions they work in. In the training simulator, the operators must work within an atmosphere as much like that which they regularly work in - including the type of displays they see, the keyboards used, the sequence of actions that are used to do switching, etc. In addition, the simulator must provide displays of network voltages, MW flows, and breaker status that are exactly as they would occur in the real world.

To accomplish these objectives, the operators use a replica of the actual EMS used in their operations department and this replica is attached to a model of the power system that includes dynamic generator models together with a power flow model of the transmission system. The power system model must be run on a very high performance processing unit so that it will be able to run the models “in real time” and provide a realistic simulation for the trainee. Attached also is a training instructor console so that problems can be prepared and presented to the operator trainee.

Some of the training scenarios that operators can be taken through with a modern OTS include handling overloads, loss of transmission lines or generators, emergency start up of generators, load shedding, voltage collapse, etc.