Piotr KAPLER

Warsaw University of Technology, Electrical Power Engineering Institute

doi:10.15199/48.2016.12.69

Possibility of nodal price usage as a signal to shift power load in time

Abstract. *The article presents possibility of nodal price usage as a signal acting stimulus to shift power load in time. Relationships between power system conditions and nodal prices were included. Furthermore, results of nodal prices variability simulation in an example power system model were posted. Power shifting possibilities without deterioration of individual consumers comfort were proposed. Also advantages and disadvantages of nodal price usage were shown.*

Streszczenie. *W artykule przedstawiono możliwość wykorzystania ceny węzłowej jako bodźca do przesunięcia poboru mocy w czasie. Zawarto związki cen węzłowych z warunkami pracy systemu elektroenergetycznego. Zamieszczono wyniki symulacji zmienności wartości cen węzłowych w systemie testowym. Zaproponowano też możliwości przesunięcia poboru mocy przez odbiorców indywidualnych bez pogorszenia ich komfortu. Ukazano zalety i wady stosowania tych cen.* ***(Możliwość wykorzystania ceny węzłowej jako sygnału do przesunięcia poboru mocy w czasie).***

Keywords: nodal prices, LMP, individual power consumers, optimal power flow
Słowa kluczowe: ceny węzłowe, cena LMP, indywidualni odbiorcy energii elektrycznej, optymalny rozpływ mocy

Introduction

Electric Power System (EPS) is a set of components used to production, transfer and distribution of electrical energy. Very often it covers large territory and acts an important role in the process of satisfy humans necessity in the scope of electricity usage. His final elements are electrical energy receivers used by an individual consumers. One of the characteristic features of EPS is a continuous subjection to changes that covers work states as well as evolutionary changes which are succession of technology development. Furthermore, an impact of other non-technical factors like law, society and policy can be also seen.

During discussions about further development of every EPS frequently an idea of shifting power load is coming back. According to this concept, every power consumer can freely (voluntarily) shift his load from the time slots with high price to the another time slots when the price is lower. In this way system load profile can be much more smoother. Peaks can be partially reduced and valleys can be filled. With this approach two-sided benefits can occur - receiver is used by the consumer but during lower price of energy and EPS has much aligned profile which decreases necessity of additional sources usage.

To make sure that load shifting is possible and profitable, each individual power consumer must have a special stimulus to action signal. Nodal price can be one of such signals.

Until now many power consumers were accustomed to one, uniform price for electricity. Usage of this model of energy market excludes simultaneous respect of power systems laws (represented by load flow calculations) and the laws of economics (represented by law of supply and demand). Abandonment from that market towards usage of nodal prices can allow each power consumer to realize that production and transfer of electrical energy for a given distance cannot cost the same in each place in the system and in every time slot (for example during one day).

In the literature usually occurs several terms relating to the same price. It can be nodal price [1], also known as LMP (Locational Marginal Pricing), short-term nodal price or spot price [2]. The idea of introduction such price is not new. It was first presented in 1979 [3]. Relationship between nodal pricing and optimal power flow task (OPF) was presented first by Schweppe in 1982.

Very often these prices are determined only for the transmission networks, although there is also a version for distribution networks called D-LMP (Distribution Locational Marginal Pricing) [4]. Each of the nodes in the network represents the physical location of the area where generation or/and load of power occurs [5]. The differences in prices between nodes are related to the cost of energy supply.

Nodal price

Nodal price (LMP) is defined as the minimal change of the cost of balancing the demand in electric power system which was caused by changing the load power at given node [6]. It can be described by following formula (1):

$$LMP_i = \frac{\partial K(P_{Gi})}{\partial P_{Li}} \qquad (1)$$

where: LMP_i - nodal price in node i, $K(P_{Gi})$ - the cost of balancing the demand, P_{Li} - active power load in the node i

Value of LMP reflects various factors which affect to the cost of delivering energy to the group of consumers. These factors are: consumers location relative to energy source (power plant), current hour of the day, congestion of network elements (lines and transformers) and networks losses. Among all these elements the major influence on the LMP values has congestion of elements [7]. Effects of congestion will be seen as high LMP values on the load nodes at the same time with low LMP values on the generation nodes.

Outside technical and economic factors attention should be pay also to social factors. Nodal price may be increased during holidays as well as at the time of occurrence of unpleasant temperature for human, both high (pressure to use air conditioning) and low (pressure to use electrical heating). Nodal prices can be also used for planning electrical power system development. However, they are representing short-term and retrospective signal [8] but the taken on decisions will have long-term consequences.

Nodal prices were implemented for the first time in New Zealand in 1997 [5].

Optimal power flow

As mentioned earlier, nodal prices are connected with optimal power flow task. Optimal power flow is equivalent to the setting of the operating status of EPS at the minimum value of the objective function and preserving technical restrictions [9]. OPF is a non-linear task. Total manufacturing cost is representing objective function. This function can be described by using generated active power and generation units prices. Minimization is done while maintaining both equality and inequality constraints [10]. Optimal power flow can be solved in AC or DC version.

Optimal power flows are usually performed separately for each hour of the day. Thanks to that equality of nodal price for active power and energy price can be assumed by constancy received power [9].

The final LMP value can be decomposed into several components, which are related with the costs of network losses, branches limitations (resulting from permissible lines and transformers load) and voltage limitations (resulting from permissible voltages).

Nodal prices variability simulation

In order to perform nodal prices variability simulations MATPOWER package were used [11]. It is successfully used for years both worldwide and Poland [12] by researchers and educators. Main advantages of this software are: fast work (application is working on m-files in Matlab or Octave environment), easy input data modification (despite the lack of graphical user interface) and license type (GNU license until version 5,0), Furthermore, MATPOWER includes an examples of power system test cases, both small (several nodes) and very large (several thousand nodes). Except optimal power flow calculations, MATPOWER can perform also traditional power flows (AC, using Newton, Gauss-Seidel and Fast Decoupled algorithms), DC power flows and solution of Unit Commitment task.

To study nodal price variability test case known as IEEE 24 Bus Reliability Test System [13] was selected. This is a very popular test system used for years to perform mainly power systems reliability analysis. All basic data of the system where included in the MATPOWER package. They where: nodal data (type of node, active and reactive demand power, voltage magnitude expressed in per units, voltage angle), generators data (active and reactive generated power, minimum and maximum active and reactive power limitations, unit status), branch data (resistance, reactance) and data needed to perform optimal power flow (cost function of each generation unit). The choice of widely available test system allows for easy comparison of results and calculations as well as discussions on the proposed solutions. All this advantages favors using power system test cases by many researchers.

The test system consisted of 24 nodes whereof 7 nodes where PQ type (receiving nodes, active and reactive power are given). It was assumed that individual power consumers where connected to that nodes. In the basic state (taken from [13]) active power received equal 2850 MW, generated - 3405 MW. Furthermore, the test case consists of 33 generation units, 38 branches and 5 transformers.

Costs for each generator unit are presented as a second-degree polynomial, which is an approximation of characteristics of the manufacturing costs of the source. It can be described by following formula (2):

$$f(p) = c_n p^n + ... + c_1 p + c_0 \quad (2)$$

where: f(p) - operating cost (expressed in $/hr), c - cost coefficients of given generation unit, n - polynomial degree, p - active power generated (expressed in MW)

The values of nodal prices are the results of calculating optimal power flow task. In order to better illustrate how price values were changing in the given network, simulation was divided into four seasons (winter, spring, summer and autumn), and in each of those seasons a typical week consisted of 5 working days (from Monday to Friday) and 2 days of weekend (Saturday and Sunday) has been designated. In turn, for each typical day and every hour OPF was solved. The results of this action were LMP P prices (for active power, expressed in $/MWh) and LMP Q prices (for reactive power, expressed in $/MVarh). Due to very large volume of obtained results the article presents only LMP P prices variability for winter and summer when the biggest discrepancy in power demand occurred.

Figure 1 presents active power demand variability in the tested power system for winter and working days during a typical week. It can be seen that, for example on Monday the greatest power demand occurred at 17:00. During this time, assumed active power load was equal 3136,5 MW and assumed reactive power load - 643,8 MVar. Generation of active and reactive power was 3202,7 MW and 539,4 MVar respectively.

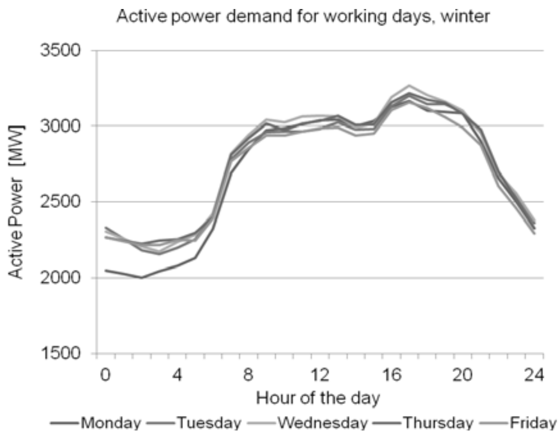

Fig. 1. Active power demand in the tested system during typical week (working days), winter

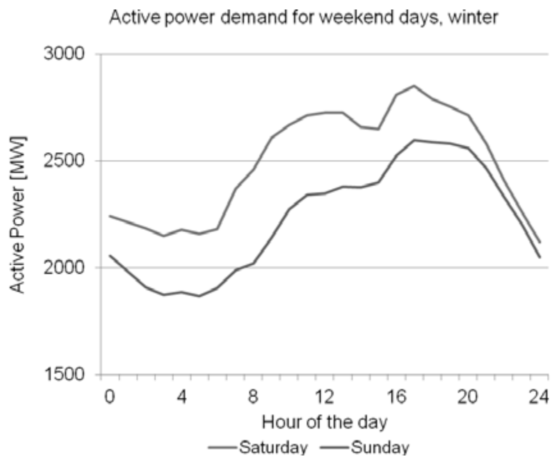

Fig. 2. Active power demand in the tested system during typical week (weekend days), winter

Analyzing Figure 1 it can be seen the smallest power load occurred on Monday during the night valley. In the next days the nature of the load curve was comparable. The greatest power load during peak time took place on Wednesday. Figure 2 shows the variability of active power demand in the tested system during the winter for the weekend days. In comparison to the working days (from the same week) it can be seen that peak demand was lower this time. On Saturday at 17:00 assumed active power load was equal 2852,2 MW while on Sunday - 2598,4 MW.

Figure 3 presents variability of nodal prices for active power (LMP P) in selected nodes 3,4 and 5. Characteristic feature of obtained prices is their shape which is very similar to the shapes of demand power from the same day like on Figure 1. Nodal prices were highest during the greatest power load (afternoon peak), while the lowest in the night valley.

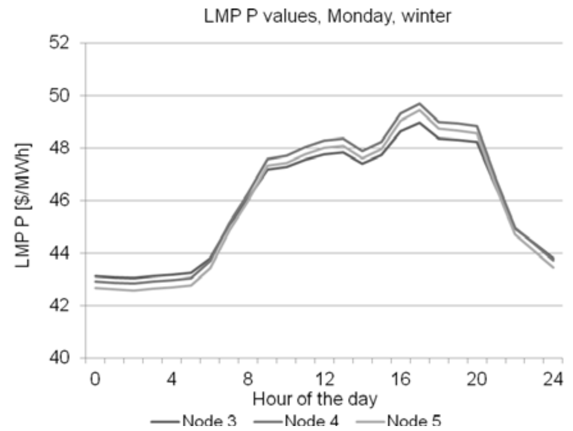

Fig. 3. LMP P values for selected working day (Monday), winter

As mentioned earlier, nodal price is also associated with power demand location relative to the source (generator). The result of this relationship is the variation of prices in every node of the given sample test system. The biggest differences between the nodal prices occurred in the vicinity of peak load period. At other times the differences were lower. It can be seen that for a typical working day nodal price values were ranged from 42,616 to 49,708 $/MWh.

During weekend days the most discrepancy between nodal prices took place in the night valley and before afternoon peak. However, due to the lower power demand at that time nodal prices have also decreased. In this case the range of LMP P was from 42,828 to 46,319 $/MWh. It was illustrated in Figure 4.

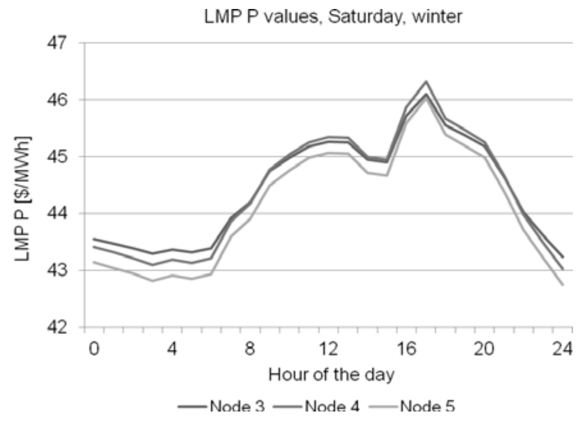

Fig. 4. LMP P values for selected weekend day (Saturday), winter

The next Figures 5 and 6 are presenting active power demand for a selected typical week during summer. Unlike the winter, in the summer can be observed much earlier occurrence of peak load (for both working and weekend days). It was caused mainly by the temperature and changes in people activities (for example holidays).

It should be noted that during the summer time, despite lower active power demand, individual consumers may want to increase air conditioning devices usage. Consequently nodal prices values can be higher.

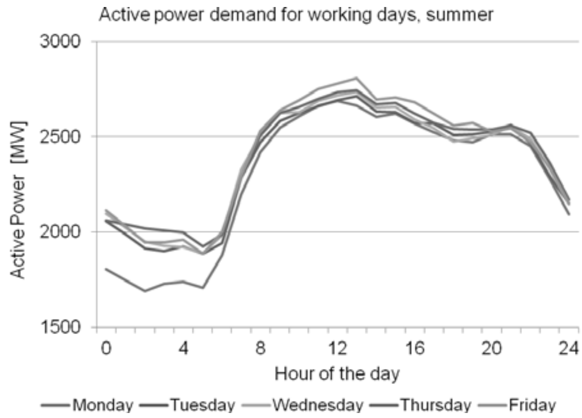

Fig. 5. Active power demand in the tested system during typical week (working days), summer

For selected week in tested power system the greatest load occurred on Friday at 13:00. Assumed active power load was equal 2806,7 MW. The reduced power demand caused that nodal prices were lower than in winter. Figure 7 is illustrating LMP P prices for active power in nodes 3,4 and 5. This time prices were ranged between 42,097 and 45,144 $/MWh. In comparison to the winter time, the highest nodal price is 4,564 $/MWh less.

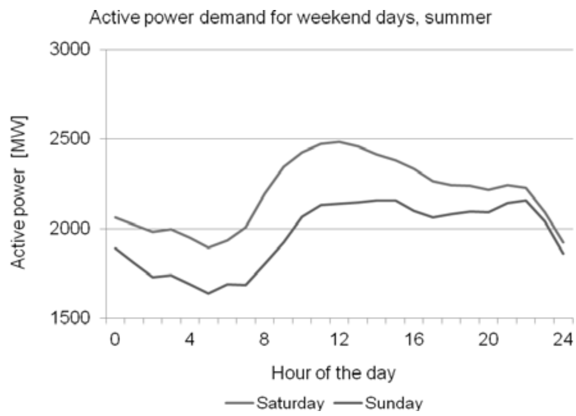

Fig. 6. Active power demand in the tested system during typical week (weekend days), summer

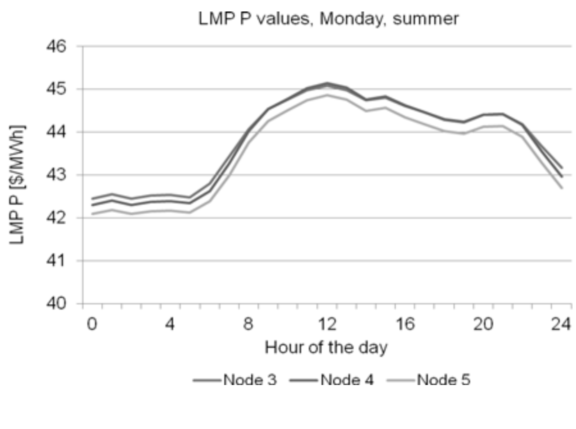

Fig. 7. LMP P values for selected working day (Monday), summer

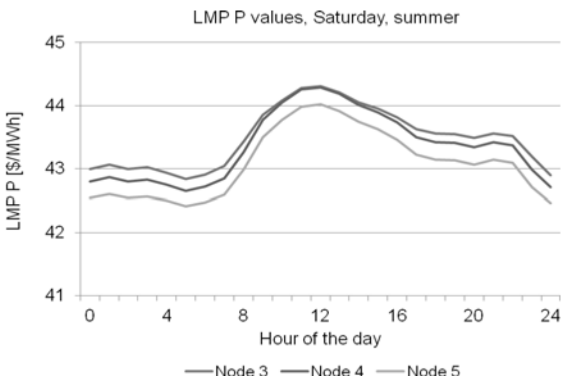

Fig. 8. LMP P values for selected weekend day (Saturday), summer

Figure 8 is presenting variability of nodal prices for active power in a typical weekend days during summer (in this example for Saturday only). LMP P values ranged from 42,475 to 44,291 $/MWh this time.

In tested power system, for all nodes LMP P prices were slightly higher than 40 $/MWh. There were no big differences between them. Also it must be noticed that in the real network greater variation of prices can be observed due to condition of elements (for example congestion of power lines) and larger distances between power consumers and generators.

Possibilities of load shifting

In the case of replacement of fixed prices for electricity by new dynamic changing in time and space (nodes) nodal prices there will be possibility of partial load shifting to the another period. This action may be performed by using given electrical energy receiver in a new time slot when (at user location) there is a new, lower price compared to the previous time slot. As mentioned earlier, nodal price can be treated as a stimulatory signal for load shifting.

First of all, every individual power consumer must be aware of laws that ruled in power system. The next step is to learn how nodal prices are varying during given period of time (year season, week or day) at consumers location.

One of the largest target group who could participate in load shifting are residential power consumers. Initially they can be split into two subgroups - employed persons and unemployed persons (retirees, pensioners and unemployed).

Consumers included among the first subgroup can use receivers only in the morning (before work), after work (late afternoon) and in the evening. Appliances that can be shifted are for example washing machine and dishwasher. It should be noticed that changing time slot of usage should not cause significant discomfort for most people. Therefore they could use them in the morning (between 5:00 and 8:00) or in the evening (between 20:00 and 22:00). For an example working day during winter, LMP P value at 6:00 was 43,431 $/MWh, whereas at 7:00 - 44,867 $/MWh. Consumer who is running given appliance (which is working for example 1 hour) must be aware of nodal price growth during one working cycle. Starting the same appliance later at 16:00, current nodal price will equal 49,052 $/MWh, while at next hour 49,439 $/MWh. For above cases, the difference between the prices at the end of working cycle will be 4,572 $/MWh. The savings are not so big, but considering the fact that consumer will need to regularly use given appliance the financial gain can be worth for some people. In this way financial benefits are the results of changing previous habits in electricity usage.

The second subgroup has potentially wider scope in the range of shifting power load to another time slot. Unemployed can additionally start to run selected appliances during the working day for example between 13:00 and 14:00. For this case nodal price was varying from 48,371 $/MWh to 47,872 $/MWh.

Except residential power consumers also industrial and commercial can be considered. However, for them shifting of load may be much more difficult due to the carried out technological processes. As authors of work [14] claimed shifting work schedule in the office building of 1 hour causes reduction of monthly electricity bills from 1% to 3%. This observation may be useful for building managers who want to reduce power demand.

Also psychological factor [15] may be an argument for using nodal price as a stimulus signal to shift load. In this case, when individual consumer will know the values of nodal prices and their unit he can immediately connect it with spending money. As a result every power consumer will be able to decide whether a change in the existing habits in the electricity usage is worth a certain amount of money.

Conclusions and summary

As mentioned above, nodal price can be used as a signal acting stimulus to shift power load into another time slot when prices can be lower. Usage of nodal prices is associated with many advantages. Some of them are: very good representation of the given network conditions, ease to justify the values of every price component, also possibility to use for the location analysis of new power sources in the system. However, utilization of nodal prices can cause some disadvantages. First one is opposition from individual power consumers which are connected by the congested network elements or they are far away from the power sources. Another obstacle may be the necessity of determining the LMP values for every hour of the day. Its values depends not only on economic factors, but also technical. In addition some of the power networks have a lot of nodes. In this case determining nodal prices for each of them can be complicated [16]. Generally, optimal power flow is a task with high degree of complexity [17].

All power consumers connected to the given node will affect on the final LMP value. Therefore there is a risk that if some of them will not participate in load shifting then nodal price can be still too high to be considered as a stimulus signal. Furthermore, there is an interaction between power load and nodal price - after shifting load a new LMP price will occur at given location.

For residential power consumers economic issues can play a meaningful role in making decision about load shifting. Unemployed consumers (with low income) may be interested in shifting load to get some financial gain after month or year. Stimulus signal will enable more conscious and effective energy usage especially in residential sector which considered in macroscopic scale can have a significant impact to the power system.

In conclusion, usage of nodal prices, despite some disadvantages, may be very useful to perform power systems analysis. Therefore this price can be regarded as a signal acting stimulus to shift power load into another period.

The article has been financed with founds on statutory activities.

***Author**: mgr inż. Piotr Kapler, Warsaw University of Technology, Electrical Power Engineering Institute, ul. Koszykowa 75, 00-662 Warsaw,E-mail:piotr.kapler@ien.pw.edu.pl*

REFERENCES

[1] Kirschen D. S., Strbac G., Fundamentals of Power System Economics, Wiley, (2004)
[2] Bil J., Ceny węzłowe jako mechanizm zarządzania ograniczeniami w systemie elektroenergetycznym, *Biuletyn Urzędu Regulacji Energetyki*, 44, (2005), nr 6, 108-111
[3] Rau N. S., Optimization Principles: Practical Applications to the Operation and Markets of the Electrical Power Industry, (2003)
[4] Sahriatzadeh F., Nirbhavane P., Srivastava A. K., Locational Marginal Price for Distribution System Considering Demand Response, *North American Power Symposium (NAPS)*, (2012)
[5] Leuthold F., Rumiantseva I., Weigt H., Jeske T., Von Hirschhausen Ch., Nodal Pricing in the German Electricity Sector - A Welfare Economics Analysis, with Particular Reference to Implementing Offshore Wind Capacities, *Trends in German and European Electricity Working Papers,* (2005)
[6] Korab R., Ceny (i stawki) węzłowe - harmonizacja rozwiązań rynkowych z nowymi trendami rozwojowymi, *ActaEnergetica,*(2009), nr 2, 31-40
[7] Singh K., Padhy N. P., Sharma J., Influence of Price Responsive Demand Shifting Bidding on Congestion and LMP in Pool-Based Day-Ahead Electricity Markets, *IEEE Transactions on Power System,* 26*,* (2011), No. 2, 886-896
[8] Hausman E., Fagan R., White D., Takahashi K., Napoleon A., LMP Electricity Markets: Market Operations, Market Power and Value for Consumers, *Synapse Energy Economics,* (2006)
[9] Żmuda K., Elektroenergetyczne układy przesyłowe i rozdzielcze. Wybrane zagadnienia z przykładami, Wydawnictwa Politechniki Śląskiej, (2012)
[10] Ziemianek S., Stany ustalone w systemach elektroenergetycznych, Oficyna Wydawnicza Politechniki Warszawskiej, (2014)
[11] Zimmerman R. D., Murillo-Sanchez C. E., Thomas R. J., MATPOWER: Steady-State Operations, Planning, and Analysis Tool for Power Systems Research and Education, *IEEE Transactions on Power Systems,* 26, (2011), No. 1, 12-19
[12] Korab R., Żmuda K., Kocot H., Planowanie pracy jednostek wytwórczych na rynku energii elektrycznej - przegląd stosowanych metod, *Prace Naukowe Politechniki Śląskiej. Elektryka*, 3, (2009), 7-31
[13] http://www.pserc.cornell.edu//matpower/
[14] Yalcintas M., Hagen W. T., Kaya A., An analysis of load reduction and load shifting techniques in commercial and industrial buildings under dynamic electricity pricing schedules, *Energy and Buildings,* 88, (2015), 15-24
[15] Billewicz K., Skuteczność DSR - między bodźcem a reakcją, *Przegląd Elektrotechniczny*, 88, (2012), nr 9a, 308-314
[16] Leevongwat I., Rastgoufard P., Kaminsky J., Status of Deregulation and Locational Marginal Pricing in Power Markets, *40th Southeastern Symposium on System Theory*, (2008)
[17] Przygrodzki M., Turczak R., Gwóźdź R., Kałuża S., Ocena zdolności przyłączeniowych Krajowego Systemu Przesyłowego w perspektywie długoterminowej, *Przegląd Elektrotechniczny*, 90, (2014), nr 7, 123-126