Elektrotehniški vestnik 73(1): 64-70, 2006
Electrotechnical Review: Ljubljana, Slovenija

New perspectives for power transmission in the European liberalized electricity market and possible role of four-phase systems

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Abstract. Production outsourcing and transmission privatization are emerging trends in the European liberalized electricity market. Transmission privatization can be a valuable opportunity of expansion for power system operators, but also an economically convenient choice for large industrial customers, that can avoid the pay-tolls due to the public transmission grids by directly connecting their production plants to the drawing power plants through non-institutional lines (the so-called merchant lines). In this new scenario, the four-phase AC transmission can be an interesting alternative to the three-phase AC and DC power transmission. This paper discusses the main features of the four-phase connection and the role it could play in the European electricity market.

Key words: power transmission, merchant lines, direct lines, four-phase transmission.

1 Introduction

The original function of the national transmission grids was to collect the power produced in large power plants and carry it to the electrical stations located throughout the country to allow the subsequent supply of electricity to end users through high-voltage (around 100 kV), medium voltage and low-voltage distribution lines.

In Europe, transmission grids of neighbouring developed countries were connected in parallel for the first time in 1960 (Fig. 1). During the period 1960-1987 the goal of the interconnection of the national grids was to guarantee reciprocal reserve and assistance in the event of large perturbations.

During the period 1970-1997, as local oppositions (mainly related to the so-called nimby syndrome) to the construction of new power plants were growing, the European transmission grid supported also long-term contracts guaranteeing power among large electrical companies. An example is the contract drawn up by ENEL and EDF with which France bound itself to sell energy to Italy, whose situation was aggravated by abolishing nuclear plants as decided through the national referendum in 1987.

After starting the European open electricity market, deadlined for 1999 by the EC directive 92/96, the activity of producing electric energy has become fully free and competitive, and so has its sale to “eligible” customers. In this new scenario the transmission grids, properly regulated and controlled by operators, which can also be owners (Transmission System Operator - TSO) or not (Independent System Operator - ISO), assume also a new function, that might be regarded as the main one, of primary systems to transfer electric energy.

Energy is either directly purchased/sold, in agreement with bilateral contracts, or indirectly, through national stock markets, between producers and eligible customers, both of them wherever placed within the Community.

Not all of the EC member countries can meet their power demand with their home production. Figure 2 shows that Italy, in particular, is at present the most import-dependent country in the EC. Since in the future the nimby syndrome will probably spread everywhere throughout the Community, the countries that will not develop a sufficient home production of electric energy (either conventional, nuclear, or renewable) will have to outsource production. This will be done by building new power plants or purchasing existing ones in more “compliant” countries, like large power companies have already been doing for some years in Eastern Europe, i.e. Bulgaria, Romania, Slovakia, Poland, Ukraine, Russia, etc. Probably, this process will boost transmission privatization, which might allow avoiding control of the TSOs and the relevant pay tolls.

In this fast-evolving scenario it is possible to guess the development of new generation transmission lines built over relatively long distances by privates or by power system operators, and characterised by:

- low construction cost/MW,
- low operating cost,
- easy technical integration with the national grids,
- high reliability (remember the recent blackouts in Europe and North America), and
- low environmental impact.

Received 4. June, 2005
Review 13. January, 2006

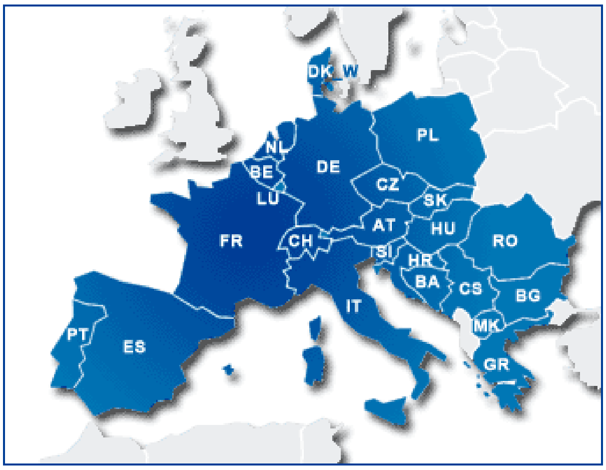


Figure 1. Interconnected power systems in Europe (UCTE).

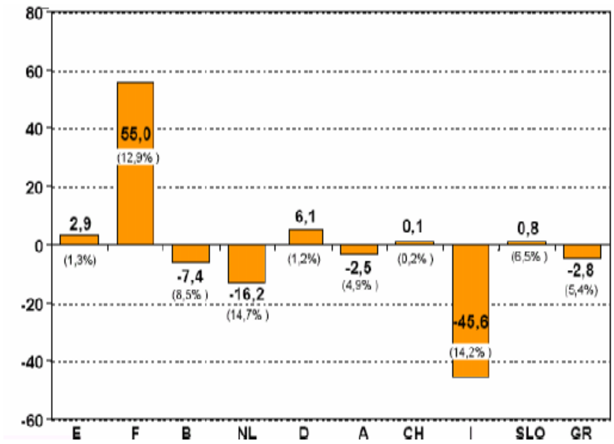


Figure 2. 2004 import/export balance. Figures are in TWh. In round brackets: per cent value referred to the requirements of each country.

2 Merchant lines

2.1 Regulation

The term "merchant lines" (or "direct lines") is used to indicate non-institutional interconnections, which can be built and owned by privates or power system operators. The EC directive 92/96 defines "direct line" a line complementary to the interconnected grid (article 2, paragraph 12). Article 21 includes instructions for the member countries to formulate proper criteria for the construction of direct lines. The EC regulation 1228/03 states that the direct lines are exempted from the dispositions of the EC directive 92/96 that guarantee the access to the network (third party access). This means that the direct lines can be partly "reserved" or, in other words, their owners can enjoy a "priority access". The new EC directive 54/03, which replaced the EC 92/96, did not modify the aspects concerning the merchant (or direct) lines.

The EC directive 92/96 has been differently put into practice by the member countries. Italy, the maximum importing country, is for instance very interested in the development of interconnections with the neighbouring countries and in new perspectives of power transmission in Europe. Its position might considerably affect the future trends.

In full agreement with the concepts of the EC directive 92/96, the Italian law 79/99 (called the Bersani law) defines the direct line as an "electric line connecting a production centre with a load centre independently on the transmission and distribution system". It also specifies that it is the ISO's duty to set technical rules for designing, building and operating direct lines, with the aim to properly connect them to the national transmission grid.

In the Italian regulation, there are some distinctions made between the merchant lines realised by power system operators and those realised by privates. For power system operators that construct new lines or expand the existing ones in agreement with the development plan of the national transmission grid scheduled by the ISO, the deliberation 151/02 of the Italian regulatory agency (AEEG) states that the right of priority access is granted case by case, for the period of ten years, for the maximum capacity of 800 MW and up to 80% of the overall transmission capacity.

As foreseen by the law 290/03 (called Marzano law), the priority access for the privates is granted by the Ministry of Productive Activities, in agreement with the regulatory agency, for the period between 10 and 20 years and for the maximum transmission capacity between 50% and 80%.

2.2 Some remarks

1) The proposed Italian merchant lines fully agree with the laissez-faire policy characterizing the EC energy policy which encourages competition and access to foreign markets by means of an easier access of operators to power transmission infrastructures.
2) The merchant lines are by all means a complementary tool that involves both opportunities and risks. The former are contribution to import development, access to markets with a lower power price, access to non-nimby areas and/or areas provided with valuable resources (for example the Albanian hydro or the gas available in North Africa). The latter are capital-intensive and nimby-subject activity.
3) The investments can be affected by the growth of the home generation capacity or price increase in the drawing markets.
4) New dominating groups could emerge. A recent analysis from October 2004 shows that the merchant projects selected by the Italian ISO were shared out as follows: ENEL Production (Italy): 17%, TERNA (Italy): 7%, EGL (Switzerland): 15%, TIWAG (Austria): 7%, AGSM Verona (Italy): 7%, Burgo paper mills: 4%, other operators: 43%. These data

show that the power system operators take the lion's share.

3 Four-phase power transmission

The proposal of high-phase transmission in power systems, instead of the usual three-phase (3P), is not novel. Advantages of a higher number of phases are higher transmission capacity, lower phase-to-phase voltage, compact overhead lines, etc. [1-8]. In the past, there have been investigated especially 6P or 12P systems because of their easy integration in the existing 3P nets, which can be done by changing connections of 3P transformers. Disadvantages of the practical realization of systems with a high number of phases are difficult phase-transposition, complex towers structure, etc.

Recently, 4P transmission (Fig. 3) has been also investigated [9-13]. Its main features, discussed in the following paragraphs, make it a very interesting alternative to 3P AC and DC transmission for new high-capacity transmission lines.

3.1 Technical integration with three-phase systems

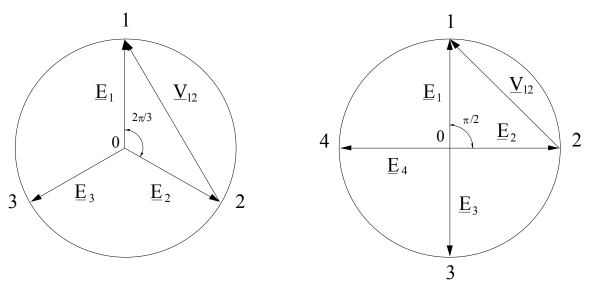


Figure 3. Voltage vectors in 3P and 4P systems.

Fig. 3 shows the voltage vectors in 3P and 4P systems. Phase-conversion from three to four (and vice-versa) is not a problem. It can be arranged by proper well-known transformer connections that have been used in the railway industry for many years [12]. The most popular are the Scott and Le Blanc connections [14]. Both the double Scott or double Le Blanc arrangement with a common neutral point allows an easy reaching of the goal (Fig. 4). These connections are reversible and thus suitable to transform from 3P to 4P and vice-versa. Recently, simpler solutions with only one special four-legs transformer have been proposed allowing direct coupling of 3P and 4P transmission [10].

A four-phase line (4PL) connecting two 3P networks with transformers of the above listed types is depicted in Fig. 5. Note that integration of a 4PL in a 3P power system is simpler than integration of a DC line.

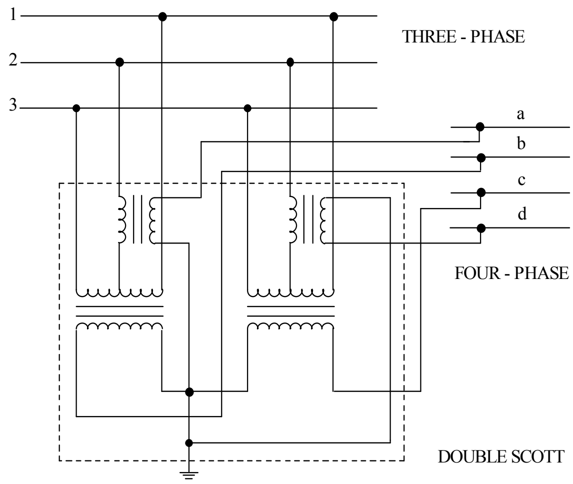


Figure 4. Conversion between 3P and 4P systems through a double Scott transformer.

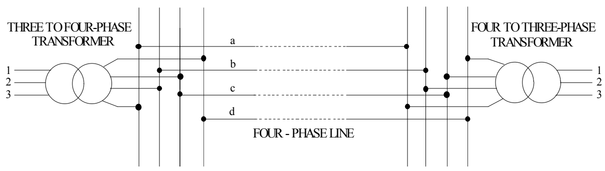


Figure 5. Four-phase line connecting two 3P systems.

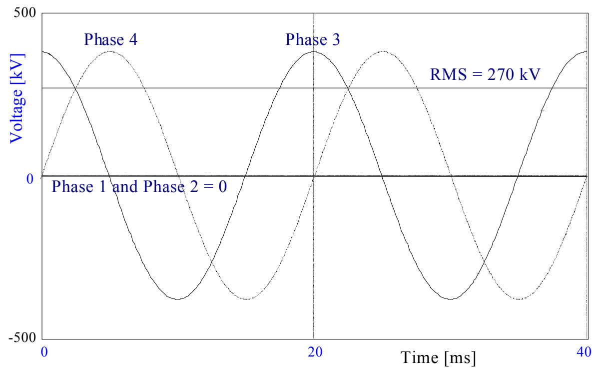
3.2 Reliability

Power transmission reliability of 4PLs is higher than of 3PLs because of the power that can still flow in case of one-phase-to-ground faults (the most frequent faults in transmission networks). In 3P systems, single-phase tripping causes unacceptable unbalanced operation for which reason single-phase faults usually result in the full (3P) line opening and power transmission drops to zero.

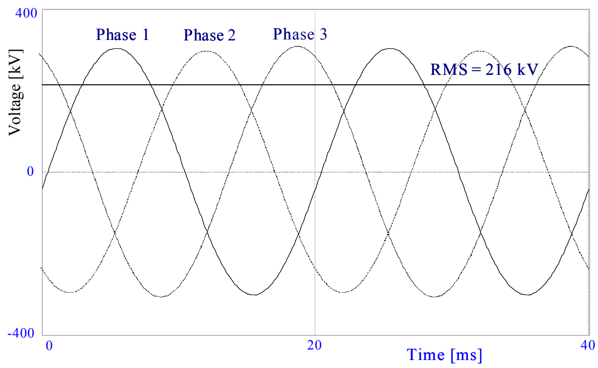
The 4P transmission (that can be viewed as made up of two independent and phase-opposite 2P systems, each with a 90° angle between the two voltages) maintains an acceptable voltage imbalance at both 3P sides even when two properly selected phases are tripped (Fig. 6). In such case, the transmissible power remains between 50% and 100%, depending on individual local conditions (pre-fault load, duration of the emergency operation, etc.).

As shown in Fig. 7, during the operation with only two phases a zero-sequence current is present in the 4PL (but not in the 3P sides). If this situation has to remain for long time, an adequate underground wire or overhead grounding-wire connecting the individual towers may be necessary.

In conclusion, as far as power transmission reliability is considered, the 4PL can be compared with the double 3PL (2x3PL) rather than with the single one. Note that the high transmission reliability of 4PLs can be very important in avoiding a full system blackout, especially in case of weak critical connections. An example is the large blackout that occurred in Italy in September 2003, caused by a phase-to-ground fault on a 380 kV line connecting the Italian and Swiss power systems.



a) phase-to-ground voltages in the 4P line



b) phase-to-ground voltages in both 3P sides

Figure 6. Operation with only two phases.

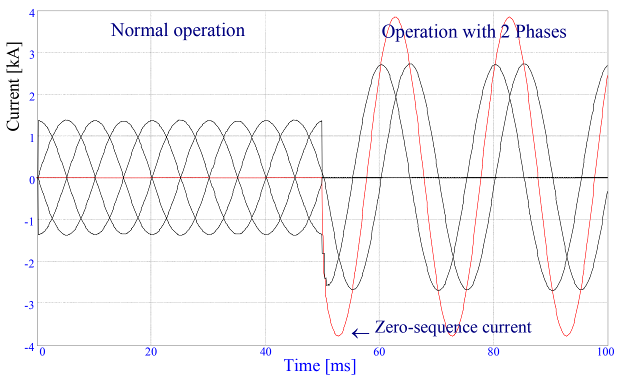


Figure 7. Four-phase line currents: normal operation (left) and operation with two phases and same power transmitted (right).

4 Comparison between 4P and 3P transmission lines

Comparing 3P and 4P transmission lines to find which is the most convenient solution from the technical point of view is not trivial. The result depends very much on parameters (voltages, current, physical dimensions, etc.) assumed to be equal in the two cases.

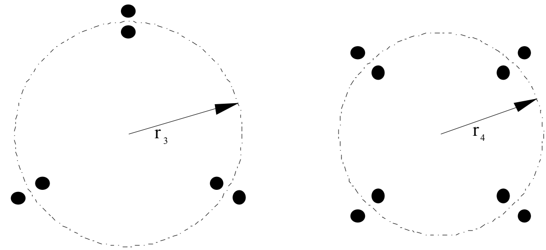


Figure 8. 3P and 4P symmetrical wires arrangements with two wires per phase.

Let's compare a 3PL and 4PL, both symmetrical as depicted in Fig. 8, with the same surge impedance, voltage gradient between adjacent phases and wires per phase (the last assumption is justified by the limited number of standard sections used and by the small difference between the line currents, as shown below). The surge (or characteristic) impedance is given by:

$$Z_0 = \sqrt{\frac{r + j\omega l}{g + j\omega c}} \cong \sqrt{\frac{l}{c}} = \frac{1}{2\pi} \cdot \sqrt{\frac{\mu}{\varepsilon}} \cdot \ln\frac{D}{\delta} \qquad (1)$$

Having the same wires, the two lines have the same equivalent geometric radius of each phase δ but, for the 3PL D=$\sqrt{3}\cdot$r3, while, for the 4PL D=2r4 (this result can be demonstrated through calculation of the reactive parameters, that is not reported here for the sake of brevity). It follows that the condition for the two lines to have an equal surge impedance is:

$$r_4 = 0.866\ r_3 \qquad (2)$$

so that the 4PL covers less space than the 3PL. To keep the same insulation level between adjacent phases, the following relation must then hold:

$$V_4 = 0.707\ V_3 \qquad (3)$$

Being $V_4=\sqrt{2}\ E_4$ and $V_3=\sqrt{3}\cdot E_3$ (Fig. 3), it follows:

$$E_4 = 0.866\ E_3 \qquad (4)$$

For any power transmitted, the current I_4 is then little less I_3 (I_4=0.866 I_3). Therefore, the 4PL has 15% higher load capability at thermal rating but, being the surge impedance loading (SIL) of an n-phase line:

$$P_{on} \cong n \frac{E^2}{Z_o} \quad (5)$$

the two lines have equal SIL ($P_{04} = P_{03}$). The two lines have also equal power losses (p_4=p_3), the disadvantage of one more wire in the 4PL being compensated by the reduced current.

Concerning stability, the power-angle (P-sinδ) relation of an n-phase transmission system is:

$$P = n \frac{E^2}{X_d} \sin \partial \quad (6)$$

It follows that for two systems with the same phase reactance X_d the stability limits are also the same.

In conclusion, a significant comparison between a 3PL and a 4PL, assuming an equal voltage gradient between adjacent phases and the same wires symmetrically placed as shown in Fig. 8, can be made by assuming also the same surge impedance. In this case the 4PL is more closely packed (smaller width and vertical section), reduces voltages (and thus lowers the cost for line breakers and manoeuvre and measurement equipment) and transfers the same power with equal power losses and reduced current. Also, the two lines have equal SIL (but the 4PL has greater load transmission capability at thermal rating) and stability limits[1].

In addition to the improved transmission reliability, a further advantage of the 4PL is in the reduced electromagnetic pollution. Less space between phases and lower currents reduce the magnetic field while lower voltages reduce the electric field. Yet, the cost of the 4PL is higher due to one more phase and special transformers at the line ends.

Having discussed the possibility offered by the 4PL to transfer a significant amount of power with only two phases (although for a limited time duration), it would be interesting to sketch out a comparison between the 4PL and the 2x3PL. The 4PL voltage has to be increased in order to make the transmission capability of the 4PL comparable with that of the 2x3PL.

Assuming the same nominal voltage (V_4=V_3), it follows E_4/E_3=I_4/I_3 =1.225. Assuming the same wires are used, the two lines have equal power losses and very similar surge impedance and SIL although the 4PL has smaller load transmission capability (81.6%) at the thermal rating than the 2x3PL.

Regardless of the actual space disposition of conductors, it is evident that while maintaining the same voltage gradient between adjacent phases, the 4PL can have smaller dimensions and, therefore, lower environmental impact than the 2x3PL.

Finally, the cost of the 4PL is lower because of less wires and smaller towers. Yet, the overall cost of the 4P transmission includes also special transformers and, therefore, it is competitive for line length exceeding a crossover value. A detailed cost-analysis is given in the next section.

5 Analysis of the investment cost

The cost is of course the main concern. Examples of really made 4P connections reported in the literature are scarce. According to [12], an EHV 4P connection is cheaper than an equivalent 3P when its length exceeds the crossover length in the range of 200-300 km. However, while the cost of 3P connections can be considered known up to the highest voltage levels, it is not the case with the 4P system for which there is no adequate industry experience. The cost of transformers, for instance, will largely depend on the type as well as on the ordered quantity, the line cost depends on the tower design, etc.

In our cost assessment we refer to two 380 kV connections made of:

- one 2x3PL with two terminal stations equipped with 380/132 kV step-down transformers
- corresponding 4P transmission system with one 4PL and two stations.

The lines cost is assessed by assuming equal SIL and wires per phase, properly oversized grounding wires in the 4PL, equal horizontal space arrangement but higher and heavier towers for the 2x3PL (see Tab. 2).

	5.1.1.1.1.1 2x3P	**4P**
Phase-to-phase voltage	380 kV	
Phase-to-ground voltage	220 kV	270 kV
SIL	1040 MW	
Wires per phase	ACSR: 3x585 mm^2	
Grounding wires	Steel 79 mm^2	ACSR 107 mm^2
Tower weight	16,500 kg	13,000 kg
Mean towers distance	400 m	

Table 2. Main data assumed for the 2x3P and 4P connections.

As shown in Tab. 3, the resulting cost for the 2x3PL is around 580,000 €/km (that matches very well the mean cost provided by the field-experience). The cost of

[1] Otherwise, if we compare two lines with the same wires and voltage gradient between phases and assume that they are also equally exploited (I_4=I_3), it follows: E_4/E_3=r_4/r_3=0.75, V_4=0.61V_3, but the 4PL has lower SIL ($P_{04} \cong 0.75P_{03}$, since the two surge impedances are very similar), lower stability limits and higher power losses (p_4=1.33p_3).

the 4PL is around 430,000 €/km (about 25% less). In any practical case, of course, line layout, land specifics and red-tape problems can have a significant impact on the line cost.

A realistic average cost of a 380 kV 3P power station is around 40.000 €/MVA. Yet, the extremity stations of the 4P connection will cost more because of special transformers and more breakers, disconnection switches, voltage and current transformers, etc. Assuming that:

- the cost of special transformers is 10-20% higher than the cost of traditional 3P transformers [12]
- the 4P station side has 33% more protection and measurement devices than the 3P side
- the cost of civil works and site is more or less the same in the two cases

it follows that the cost of the 4PL end stations is about 48.000 €/MVA, which is 20% more than the cost of standard 3P stations.

Based on these results, the crossover line length L_{min} can be calculated with the following equation:

$$L_{min}\text{ [km]} = 0.0538\text{ S [MVA]} \tag{7}$$

where S is the total capacity of the two terminal stations. Just for example, for a 2400 MVA capacity (two stations rated 1200 MVA each), the crossover length is 129 km meaning that the 4P connection is cheaper for line length exceeding 129 km.

	2x3PL [€/km]	**4PL [€/km]**
Wires	123.039	82.026
Two grounding wires	1.531	3.174
Wire-stretching	156.000	104.000
Ground wires stretching	12.000	12.000
Suspensions (insulators + equipment)	27.480	21.120
Towers	103.125	81.250
Foundations	54.281	36.187
Rights-of-way, damages and notarial expenses	60.000	60.000
Technical expenses for project and site work	42.257	31.375
TOTAL COST	**580.453**	**431.738**

Table 3. Investment cost for the 2x3PLs and 4PLs.

6 Conclusions

The current technical, economical and social conditions are giving rise to new trends in the European liberalized electricity market. The on-going process of production outsourcing will probably boost the construction of non-institutional lines (merchant lines), within the process of transmission privatization which fully agrees with the laissez-faire practice characterizing the current European energy policy.

Four-phase transmission lines can be regarded as a viable alternative for the construction of new interconnections over relatively long distances. They can be easily integrated in the existing three-phase networks and guarantee power transmission reliability similar to that of the double three-phase lines, with construction cost that could become competitive over a reasonably limited line length and reduced environmental impact.

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Stefano Quaia (1962) graduated in Electrical Engineering from the University of Trieste in 1988. In 1990 he joined DEEI, the Electrotechnics, Electronics and Computer Science Department of the University of Trieste, where he is now Associate Professor of Power Systems. His current research interests are in the fields of power quality, power delivery, power transmission reliability and power system restoration.

Recenzija

Peter Starič in Erik Margan: Wideband Amplifiers, Zal. Springer, P.O.Box 17, 3300 AA Dordrecht, Nizozemska, 2006, 631 strani, 440 slik, nekaj deset tabel, format 24,5×16,5 cm, trdo vezana, skupaj s CD-jem, ki je v barvah, 39.860,00 SIT, oziroma 142 €.

Knjiga je napisana tako za začetnike kot učbenik; kakor tudi kot priročnik za že izkušene načrtovalce elektronskih vezij kot knjižnica podatkov, še bolj pa za poglobitev znanja. Ko jo vidite obnemite ob vseh matematičnih izpeljavah, prikazih v slikah in podatkih v tabelah. Načrtovanje analognih vezij, kjer sta ojačanje in hitrost delovanja nadvse pomembna, je znanost, ki zahteva poglobljeno matematično obdelavo, ki jo knjiga nudi. Vrsta aplikacij, zanimivih primerov, krivulj delovanja in mnoge računalniške subrutine pa knjigo poživljajo in vlečejo bralca vedno globlje v stvar. Besedilo je razdeljeno na 7 poglavij.

V prvem poglavju je obdelan **Laplaceova transformacija**. Tej in njeni inverzni vrednosti dajeta avtorja prednost pred obdelavo z diferencialnimi enačbami pri iskanju odziva ojačevalnika v časovnem prostoru, ker temeljita na ničlah in polih, kar je uporabno tudi pri analizi v frekvenčnem prostoru, ki ga avtorja enako temeljito obravnavata. V zvezi s tem za večino vezij podajata diagrame za amplitudno, fazno in ovojnično zakasnitev v odvisnosti od frekvence, ter odziv na stopnični signal v časovnem prostoru. V vseh diagramih so podane osnovne sheme, enačbe, podatki, po potrebi pa tudi razmestitev polov, kar je zelo pripravno za vsakdanjo prakso. Tudi če bralec ne pozna tematike, se je lahko tu hitro nauči.

Sledijo vezja z induktivnimi kompenzacijami za razširitev širine pasu frekvenčnega odziva. Skozi zgodovino je opisanih mnogo sprememb, predvsem pa mnogo takih vezij. Vse kompenzacije se obravnavajo enotno in sicer tako, da so medsebojne relacije elementov, ki tvorijo vezje, izpeljane iz kota θ, ki ga tvorijo razdalje iz izhodišča do polov z realno osjo koordinatnega sistema. Te relacije določajo frekvenčne karakteristike vezja in odziv vezja na stopnični signal. Dejanske vrednosti tako izbranih elementov pa določajo v kakšno frekvenčno oziroma časovno področje spada obravnavano vezje. Na koncu poglavja, ki ima kar 117 strani, je primerjalni diagram vseh obravnavanih vezij v frekvenčnem prostoru z Butterworthovimi poli ter podoben diagram odzivov na stopnico v časovnem prostoru z Besslovimi poli.

V tretjem poglavju so opisani na 98 straneh širokopasovni ojačevalniki s polprevodniškimi elementi . Analizirani so osnovni gradniki širokopasovnih ojačevalnikov: ojačevalniki s skupnim emitorjem, bazo, impedančni pretvornik, kaskodni, diferencialni ojačevalnik in napetostni sledilnik. Vidimo več poti do izboljšanja obnašanja vezij pri visokih frekvencah.

Sledi obravnava kaskadno – zaporedno vezanih ojačevalnih stopenj in optimizacija njihovega delovanja. Prava izbira polov je najbolj pomembna za obnašanje vezja. Na vsakem koraku je jasno, kako hitro se izgubijo optimizirane lastnosti posameznih stopenj v skupnem vezju, če te niso sklopljene pravilno. To poglavje ima 71 strani.

V petem, tudi zelo dolgem poglavju na 134 straneh, so obravnavani večji integrirani sistemi. Za primer je naveden dvostopenjski ojačevalnik z induktivnimi kompenzacijami ter način kako moremo z geometrijsko sintezo prilagoditi ojačevalnik na želene karakteristike v frekvenčnem oziroma časovnem prostoru, npr. na Butterworthove ali Besslove pole. Velika pozornost je posvečena tudi visokoohmski vhodni stopnji s spojnim FET, ki se uporablja predvsem v osciloskopih in merilnih instrumentih. Poudarek je na jasni fizikalni sliki, podrobno pa je podan tudi izračun vezja za kompenzacijo negativne vhodne upornosti. Pisca obravnavata tudi visokoohmske frekvenčno kompenzirane delilnike ter vplive parazitnih induktivnosti vhodne in izhodne zanke signalov. Sledi obravnava specialnih ojačevalnikov z visoko linearnostjo ter operacijskih ojačevalnikov, kjer je poudarjena prednost tokovne negativne povratne vezave.

V šestem poglavju so na 65 straneh opisi računalniških algoritmov za analizo in sintezo filtrskih sistemov, kamor spadajo tudi širokopasovni ojačevalniki. Analiza temelji na polih, za kar so podani tudi celotni programi, ki jih je možno uporabiti z osnovnim programom Matlab. Za analizo prehodnih pojavov pa razložita pisca celotni program za hitro Fourierjevo transforfmacijo (FFT).

V zadnjem, sedmem poglavju, ki ima 45 strani, pa je veliko aplikacij algoritmov iz prejšnjega poglavja. Namenjeno je predvsem načrtovalcem analognih vezij, da se na lahek način seznanijo z uporabo računalniških metod, ki močno olajšajo matematično analizo v prvih petih poglavjih.

Knjiga je namenjena širokemu krogu. Študenti bodo v njej našli zelo lep in strnjen prikaz analize vezja na prehodne pojave ter vsega bistvenega, kar je treba upoštevati pri razvoju širokopasovnih ojačevalnikov. Inženirjem, ki take ojačevalnike razvijajo, bo knjiga koristen priročnik, predvsem zaradi številnih diagramov, kjer so vsi glavni podatki in zaradi uporabnih tabel. Uporabna bo tudi za profesorje in študente na podiplomskem študiju, saj je obravnavana snov, čeprav zelo zahtevna, tudi nenavadno jasno prikazana. Podobne knjige v literaturi o širokopasovnih ojačevalnikih ni bilo petdeset let, bili so samo posamezni članki .

Priložena zgoščenka, kjer so vsi diagrami v barvah ima še kakih 100 strani več. Poleg celotne knjige so na njej še nekateri programi, animacije in vse težje izpeljave, ki ne sodijo v knjigo. Tu najdemo tudi življenjepisa obeh avtorjev ter prikaz njihovega dela.

Čeprav je cena knjige skupaj z zgoščenko razmeroma visoka, je to delo nenadomestljivo za vse, ki se poglobljeno ukvarjajo s širokopasovnimi ojačevalniki. Do sedaj je to edina knjiga, ki tako celovito in obenem matematično temeljito obravnava to področje.

B. Zajc